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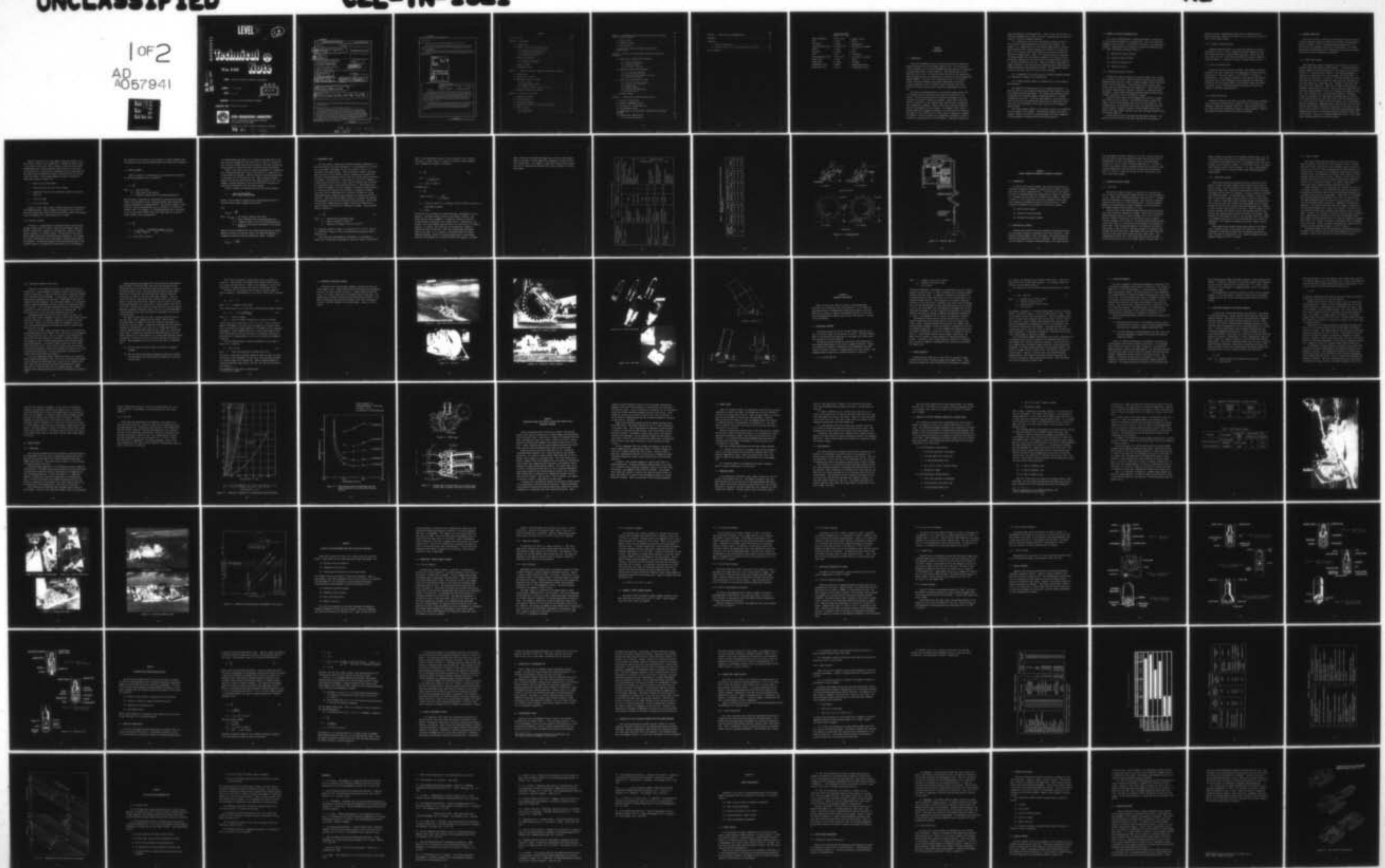

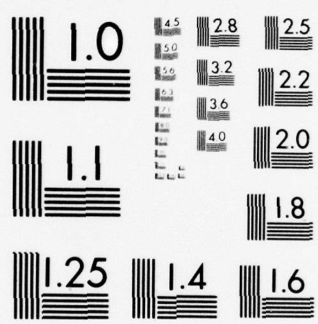

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Cables and pipelines that traverse the nearshore and surfzone regions often fail because of damage from hydrodynamic forces and anchor snags. This report discusses the technology base necessary to design and operate ocean-bottom trenching equipment for operation in sand, rock, and coral. It also reviews the state-of-the-art in all operational trenching concepts. This investigation addresses only the trenching mechanism and does not consider the platform for its support or transportation underwater. Two basic

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(1) The ladder-type mechanical trenching system using carbide cutters can (with limitations) improve the performance of the Navy's trenching capability using state-of-the-art technology; and

(2) The high-pressure waterjet trenching system utilizing the cavitation phenomenon is the development area that shows the most promise for providing significant performance improvements.

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(1) The ladder-type mechanical trenching system using carbide cutters can (with limitations) improve the performance of the Navy's trenching capability using state-of-the-art technology.

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Conversion Table
English to SI Units

degree Fahrenheit	(-32) x 0.56	=	degree celsius
foot	x 0.304	=	meters
foot/minute	x 0.0051	=	meter/second
foot-pound/cubic feet	x 4.789×10^{-5}	=	joule/cubic centimeter
gallon	x 3.785	=	liter
horsepower	x 745.69	=	watt
inch	x 25.4	=	millimeter
inch-pound/cubic inch	x 6.9×10^{-3}	=	joule/cubic centimeter
pound, force	x 4.448	=	newton
pound, mass	x 0.4536	=	kilogram
pound/square inch	x 6894.7	=	newton/square meter
pound/cubic feet	x 16.02	=	kilogram/cubic meter

CHAPTER I
BACKGROUND

1.1 INTRODUCTION

Terrestrial equipment can now excavate narrow trenches in materials ranging from sand up to and including competent rock. An investigation of this equipment, and of novel developments having potential for underwater trenching applications is being conducted. The work described in this report was done in FY-77 as a portion of the Ocean Facilities Engineering Block Program Plan under the sponsorship of the Naval Facilities Engineering Command (NAVFAC). The goal of this investigation was to (1) identify current trenching techniques that provide improvement to the Navy's trenching capability, and (2) identify future techniques that, when properly developed, would provide a significant improvement over item (1).

The type of trenching machine or the excavation method required for a job depends heavily on the particular type of rock material to be removed. Excavation machines can be classified according to the rock strengths the machine is capable of removing. Cannon (Ref 1) has classified rock material as soft, medium, hard, and very hard, according to their compressive strengths. Table 1 lists these categories along with specific rock examples in each category. For example, coral, with an average compressive strength of 6,000 psi, is classified as soft material. Some types of rock, however, have a large range of compressive strengths. For example, one type of granite has a compressive strength, σ, equal to 12,000 psi; pink granite has a σ of 32,000 psi. Therefore, granites can

range from medium to very hard material. Table 1 also lists the type of excavation equipment most likely to be used in removing specific materials from one of the four strength categories.

It is important to note that no one machine or method available is best-suited for excavating material from every rock category. For example, it is common practice to use carbide-tipped drag bit trenchers when excavating soft to medium strength rock; however, if a large soil mass is to be trenched, the carbide drag bits are often replaced with special soil digger blades. Also, if a trencher operator is trenching in medium strength rock, and suddenly encounters a very hard rock vein, he typically bypasses this area and contracts an impact breaker operator to come back and chip the vein away. Typical nearshore bottom material ranges from sand to very hard rock and, therefore, poses similar material removal problems for the underwater trencher. The envisioned nearshore trencher would then consist of either of the following:

(1) A combination of several pieces of trenching equipment designed for trenching all categories of rock material

(2) A single machine capable of trenching only a certain range of bottom material

The combination trencher would be a very complicated machine. It would no doubt be a heavy machine requiring additional weight to satisfy the extreme trenching requirements. The single trenching machine would be designed for a specified range of bottom materials (i.e., medium strength rock and coral). With the second method, a crew would have to return to the site and complete the trench route by removing the sandy area with a suction dredge, and the hard rocky area with a hydraulic impact breaker.

This latter approach appears to be the more practical for minimizing size and weight of the trencher. The nearshore trencher would be designed to operate efficiently in medium strength rock and be augmented by other methods for removing soft and very hard materials.

1.2 THEORY OF CUTTING AND BREAKING ROCK

For a better understanding of trenching techniques, a description of rock excavation mechanics is presented here. All of the excavation equipment listed in Table 1, and the novel techniques to be discussed in Chapter 5, break down the rock using one of four basic mechanisms (Ref 7). These "breakdown" mechanisms consist of:

(1) Mechanically induced stresses

(2) Thermally induced stresses

(3) Fusion and vaporization

(4) Chemical reactions

1.2.1 Mechanically Induced Stresses

Mechanically induced stresses are created by impact with, abrasion on, or erosion of the rock. When the applied stress from the excavation machine exceeds the rock's tensile or shear strength, brittle fracturing within the rock takes place. The fracturing process continues until large cracks are created and the rock breaks apart. Impact stresses can be created from percussion, implosion, explosion, or underwater spark discharges. Typical impact-producing excavation methods include impact breakers, percussive drills, and explosive charges.

Abrasion devices remove rock by dragging hard carbide or diamond bits across the rock's surface. The abrasion creates a crushed zone ahead of the bit while planing a groove into the rock behind it. The crushing action of the abrasive bits create rock chips which break off and are removed. Examples of abrasive cutter machines include coal miners, disc saws, ladder trenchers, rock saws, and some waterjets which use abrasive additives.

Erosion devices include low-speed and high-speed waterjets. Low-speed jets (30 to 650 fps) "wash away" sand and soil (also known as

hydraulic mining). High-speed waterjets (650 to 3,500 fps) rely on high-pressure water (greater than 60,000 psi) directed directly onto the rock to induce high stresses.

1.2.2 Thermally Induced Stresses

Thermally induced stresses are created when enough heat energy is absorbed by the rock to cause a differential thermal expansion of the rock crystals and grains (called thermal spalling.) Thermal spalling only weakens the rock. Some additional mechanical means is necessary to break and remove it. Flame jets are used to induce thermal stresses.

1.2.3 Fusion and Vaporization

Fusion and vaporization devices transmit large amounts of thermal energy into the rock, causing the local temperature to exceed the rock's melting point. Most rocks require 1×10^8 ft-lb/ft^3 of energy for fusion (Ref 7). Less energy is required to fuse igneous rocks (granite and basalt) than to fuse sedimentary rocks (sandstone and limestone). Vaporization of rock requires about five times more energy than needed for fusion. So far, fusion and vaporization devices are novel and limited to laboratory experimentation.

1.2.4 Chemical Reactions

Chemical reactions can be used to literally dissolve rock. Halogens, such as fluorine, have been used in chemical drills for forming holes in sandstone, limestone, and granite (Ref 8, 9). These reactions occur so fast that they set up enough heat intensity to ignite asbestos. However, the products produced from fluorine drills are harmless.

1.3 TRENCHER TERMINOLOGY

Much of this report is devoted to the discussion of two particular trencher mechanisms: mechanical ladder-type trenchers and high-pressure waterjet trenchers. Both of these methods appear applicable to the Navy's needs for underwater excavation of the nearshore. For further discussion of these methods and for comparison with alternative methods, some definitions and terminology are presented.

1.3.1 Ladder-Type Trencher

The ladder-type trencher mechanism, shown in Figures 1.1a and b, is normally pulled along behind a tracked vehicle. It is manufactured by several companies in various designs and is also known as a "chain-type trencher," or "continuous belt trencher." The trenching mechanism consists of a rigid cutter bar, drive sprocket, and cutter chain. It functions very similarly to a chain saw. The drive sprocket drives the chain down into the trench, around the rigid cutter bar, and back up to the drive sprocket in a continuous loop. Attached to the cutter chain are cutter tools called bits. These bits are made of hard material (normally carbide encased in steel). Because the total energy delivered from the trenching machine to the rock is transferred through the cutter bits, they constantly wear out during normal operation. Therefore, cutter bits are made to be replaceable by mounting them in holders or blocks attached directly to the cutter chain. When the cutting action is in the direction of forward travel (U) (Figure 1.1a), the trencher is known to be upmilling. Upmilling tends to pull the chain into the drive sprocket under tension, driving the cutting side of the chain into the work. As the cutter bar is forced into the work, the machine must supply enough draw-bar force to overcome the downward resistance and pull the cutter forward. This pull is normally supplied by tractor. Most ladder-type trenching machines use the upmilling mode.

When the chain drive is in the opposite direction (Figure 1.1b), the trencher is known to be climbmilling. Climbmilling causes tension on the inactive side of the chain, tending to slack the cutting side. Climbmilling acts to push the machine forward and out of the trench. Less draw-bar pull is required for climbmilling than for upmilling, but the machine must be sufficiently heavy to keep the cutter bar solidly inside the trench. The following symbols are used in reference to ladder-type trenchers (Figure 1.1).

d = depth of cut (trench depth)

U = forward traverse velocity of the trencher

U_t = tangential cutter bit tool speed with respect to the rigid cutter bar

ϕ = cutter bar angle

S = cutter bit spacing

Figures 1.1c and d show a wheel trencher mechanism in the upmilling and climbmilling mode. Wheel trenchers (also known as disc saws) are essentially ladder-type trenchers with the blocks and cutter bits mounted on the circumference of a wheel instead of on a chain.

1.3.2 Waterjet Trencher

A waterjet is a high-pressure, high-speed stream of water forced through a small orifice or nozzle. Water-stream pressures range from 60,000 to 100,000 psi; enough to cut through rock. Figure 1.2 shows a typical schematic of a waterjet system. A prime mover drives the hydraulic pump, which drives the high-pressure intensifier. The intensifier forces high pressure water to the nozzle, directing the stream to the workpiece. An important parameter when discussing waterjets is the standoff distance, D_J, measured from the nozzle exit to the workpiece.

The intensity of the waterjet on the workpiece is highly dependent upon the standoff distance and the medium between the nozzle and the workpiece.

1.4 SPECIFIC ENERGY

"Specific energy" is an expression used to measure the efficiency of rock-cutting machines and is defined as:

$$E = \frac{\dot{P}}{\dot{V}} \quad (1)$$

where E = specific energy

$\dot{P}$ = power input to the machine

$\dot{V}$ = volumetric removal rate of the excavated material

When the power is expressed as inch-pounds per minute and the volume removal rate expressed as cubic inches per minute, then the specific energy is expressed as inch-pounds/inch^3. The specific energy is calculated for a given cutting machine and is a measure of its ability to perform a task. For example, if a trenching machine were to use 50 hp to cut a rock trench 6 inches wide by 30 inches deep at 0.5 fpm ($\dot{V}$ = 1,080 in.^{3}/min), then from Equation 1:

$$E = \frac{\dot{P}}{\dot{V}}$$

$$E = \left(\frac{50 \text{ hp}}{1{,}080 \text{ in.}^3\text{/min}}\right)\left(\frac{33{,}000 \text{ ft-lb/min}}{\text{hp}}\right)\left(\frac{12 \text{ in.}}{\text{ft}}\right)$$

$$E = 1.83 \times 10^4 \text{ in.-lb/in.}^3$$

If another machine were able to cut a trench in the same type of rock with a specific energy less than 1.83 x 10^4 in.-lb/in.^{3}, it would be a more efficient trencher than the first machine: the lower the specific energy required to perform the task, the more efficient the machine.

Table 2 lists typical specific energy requirements for conventional rock crushing machines and is used in this report as a comparison for rating excavation equipment. Specific energy is inversely proportional to the square root of the particle size. Thus, the most efficient machines are the ones that break off the largest blocks of rock. For example, a machine designed to saw two parallel kerfs and knock out large blocks would have a very low specifc energy.

Specific energies are typically given for the overall machine:

$$E = \frac{\text{power to the machine}}{\text{unit volume excavated/time}}$$

However, the net specific energy of the cutting mechanism itself is obtained from the power consumed by the cutter.

Thus

$$E_{cutter} = \frac{K\dot{P}}{\dot{V}}$$

where E_{cutter} = net specific energy of the cutter

$\dot{P}$ = power consumed by the cutting mechanism only

$\dot{V}$ = volumetric removal rate of the excavated material

K = percent of total power distributed to the cutting mechanism

Typically as much as 80% of the total power required by the trenching machine is used for cutting the trench. The remaining 20% power is consumed by propulsion drives and mechanical losses. Therefore,

$$E_{cutter} = \frac{0.8\ \dot{P}}{\dot{V}}$$

1.5 PERFORMANCE INDEX

Once the specific energy for an excavation machine trenching in a particular material has been determined, it is then possible to calculate the cutting power requirement for any size trench as long as it is trenching in the same material. Since the specific energy is dependent upon the material being removed, specific energies may be compared for different excavating machines only if they are cutting identical materials. For example, the efficiency of a particular disc saw can be compared to a high pressure waterjet only if their specific energies were calculated for each machine while cutting identical material. Most manufacturers of excavation equipment test their machines in readily available material or in the particular material their machine is designed to excavate. Since there is no standardized test or material available for rating trenching machines, comparing them using specific energy calculations is difficult. There have been attempts, however, to normalize the specific energy parameter with the type of material being excavated. Mellor (Ref 12) describes a dimensionless performance index which normalizes the specific energy to the material's compressive strength. The performance index is defined as:

$$D = \frac{E}{\delta} \tag{2}$$

where D = dimensionless performance index

E = specific energy (in.-lb/in.^{3})

δ = compressive strength of the rock (lb/in.^{2})

If a trencher's specific energy is calculated to be 5×10^3 in.-lb/in.^{3} in 12,000 lb/in.^{2} granite, then its dimensionless performance index, D, would be 0.42.

Once D has been established for the machine, it is possible to predict the cutting power requirement for any size trench in any material.

Thus, if the same machine (with D = 0.42) were used to cut a trench 3 feet deep, 12 inches wide, at 0.5 fpm (1.5 ft^3/min) in hard sandstone with a compressive strength of 17,500 psi:

$$D = \frac{E}{\delta} \tag{2}$$

$$0.42 = \frac{E}{17{,}500 \text{ lb/in.}^2}$$

$$E = 7{,}350 \text{ in.-lb/in.}^3$$

From Equation 1:

$$E = \frac{\dot{P}}{\dot{V}}$$

$$7{,}350 \text{ in.-lb/in.}^3 = \frac{\dot{P}}{1.5 \text{ ft}^3\text{/min}}$$

$$\dot{P} = (7{,}350 \text{ in.-lb/in.}^3)\ (1.5 \text{ ft}^3\text{/min})\ (1{,}728 \text{ in.}^3\text{/ft}^3)\ (1 \text{ ft/12 in.})\ (\text{hp/33,000 ft-lb/min})$$

$$\dot{P} = 48 \text{ hp}$$

The validity of this method for establishing power requirements is still unproven. Consideration must be given to the manner in which a rock breaks and the size of fragments. In addition, D does not take into account physical limitations of the machine itself. Theoretically, the machine in the above example requires 48 hp to cut the trench in 17,500-psi material. In reality, the cutters may not be physically capable of transmitting 48 hp to the rock. Thus, the dimensionless performance index is not exact. It is, however, a convenient method for rating different machines, since D is inversely proportional to the machines efficiency (the smaller D is, the more efficient the machine). One must

keep in mind that one machine may appear more efficient than another, where in actuality it may be physically incapable of cutting certain types of materials. For example, a ripper may be more efficient than a disc saw for removing weak sandstone but totally incapable of cutting hard granite.

Table 1. Typical Rock Excavation Equipment

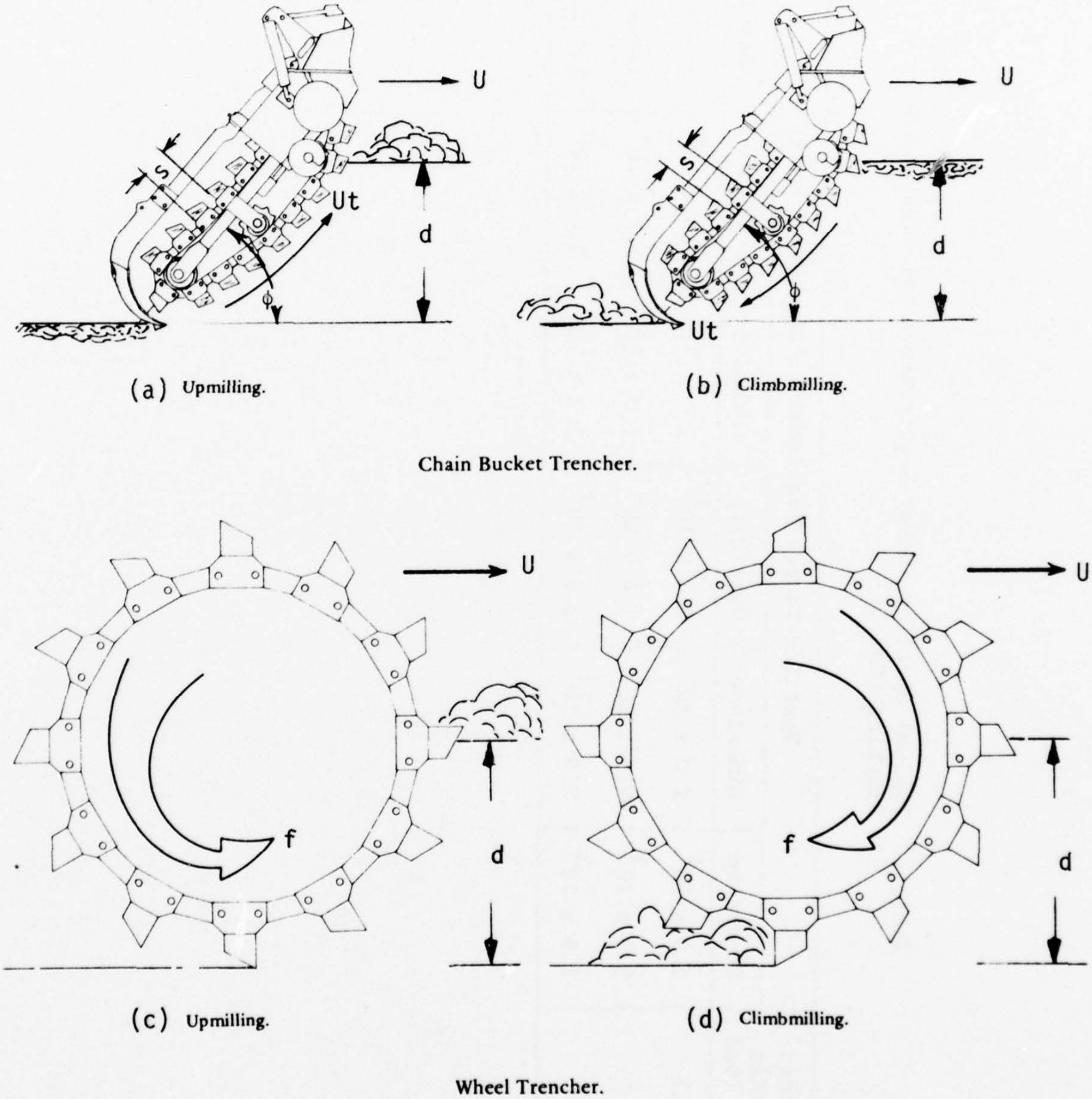
Rock Classification (based on compressive strength, σ)	Material	Compressive Strength	Reference	Excavation Equipment (ranging from soft to hard)
Soft σ = 0 to 7,000 psi	sand arctic frozen silt, frozen clay, frozen sand coal weak sandstone, limestone basalt coral	— 2,200 2,500–5,000 4,500–6,750 5,500 6,000	 2 3 4,5 5 6	Low-pressure waterjets Suction pumps and dredges Backhoes Bucket trenchers Dredges (cutterhead) Plows Medium-pressure waterjets Rippers Coal miners
Medium σ = 7,000 to 14,500 psi	medium sandstone granite	7,250 12,000	3 5	Disc saw trencher Ladder trencher Rock saws
Hard σ = 14,500 to 29,000 psi	cementitious siltstone hard sandstone	15,000 17,500	5 3	High-pressure waterjets Electrical discharge Impact breakers
Very hard σ > 29,000 psi	pink granite	32,000	4	Percussive drills Jackhammers Explosives Flame jets Chemical

Harder Material

Softer Material

Table 2. Typical Specific Energy Requirements for Conventional Crushing (Ref 11)

Crushed Particle Size (mm)	Specific Energy Requirement (in.-lb/in.^{3}) for –					
	Sandstone	Limestone	Quartzite	Granite	Shale	Basalt
0.1	2.9×10^4	2.9×10^4	3.2×10^4	3.7×10^4	4.0×10^4	5.0×10^4
1	9.3×10^3	9.3×10^3	1.0×10^4	1.2×10^4	1.3×10^4	1.8×10^4
10	2.9×10^3	2.9×10^3	3.2×10^3	3.7×10^3	4.0×10^3	5.6×10^3



(a) Upmilling.

(b) Climbmilling.

Chain Bucket Trencher.

(c) Upmilling.

(d) Climbmilling.

Wheel Trencher.

Figure 1.1. Trenching modes.

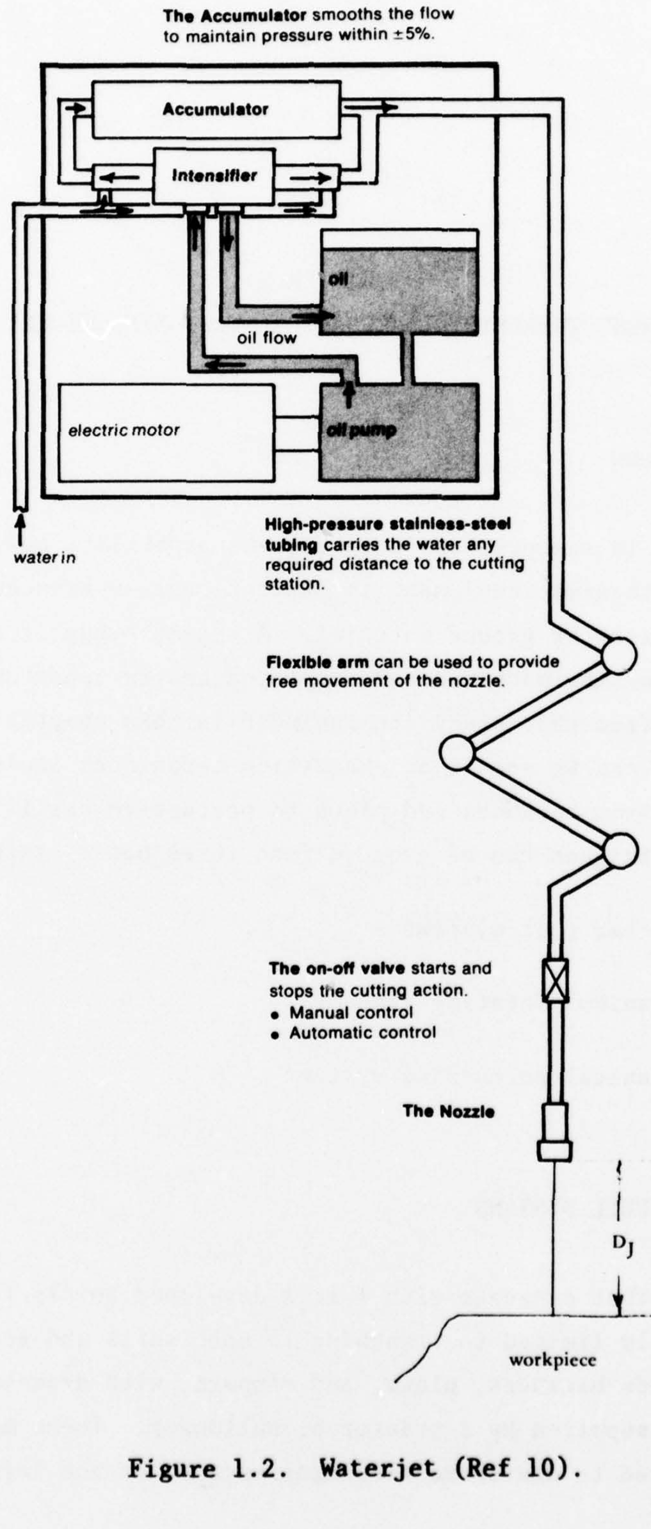


Figure 1.2. Waterjet (Ref 10).

CHAPTER 2

CURRENT TERRESTRIAL MECHANICAL TRENCHING TECHNIQUES

2.1 INTRODUCTION

As stated in the previous chapter, the capability now exists for terrestrial mechanical equipment to excavate narrow trenches in almost every type of rock or ground material. A recent study of the state-of-the-art of trenching machines was completed and is reported in Reference 13. Findings from that study are included in this chapter. Referring to Table 1, it can be seen that excavation techniques include using tools ranging from backhoes and plows to percussive drills. These mechanical techniques can be grouped into three basic systems:

(1) Draw-bar pull systems

(2) Mechanical rotating systems

(3) Mechanical percussive systems

2.2 DRAW-BAR PULL SYSTEMS

Machines that excavate with forces developed solely from the draw-bar are normally limited to trenching in soft soils and gravel. These machines include backhoes, plows, and rippers, with draw-bar pulling force usually supplied by a tractor or bulldozer. These machines are not well-adapted to nearshore trenching because of the large draw-bar

pull requirements and their inability to cut rock. Several cable plows have been used in deep ocean applications where bottom conditions are predominantly soft soils and sediments. Even in this application, draw-bar pull can be as high as 100,000 pounds (Ref 14). A study is currently in progress at CEL to minimize draw-bar pull on deep-sea cable plows by mechanically vibrating the plow through the bottom material (Ref 14). Figure 2.1 shows the concept for the vibratory plow, deep ocean, cable burial system.

2.3 MECHANICAL ROTATING SYSTEMS

2.3.1 Disc Saws

The disc saw, shown in Figure 2.2, consists of a rotating steel disc (or wheel) containing bullet-shaped carbide bit cutters attached to its rim. These saws are typically mounted on the rear end of a tracked vehicle and operated in the upmilling mode. Disc rotation is normally between 10 and 45 rpm on a 7-foot-diameter wheel. Disc saw-trenching machines are manufactured by several companies in the United States. The largest diameter wheel available is 7 feet.

Disc saws can cut most medium strength and some hard rock material up to about 20,000 psi compressive strength. Typical disc saws cutting medium strength rocks have a specific energy of 3.5×10^3 in.-lb/in.^{3}. They have, however, been used to cut hard material such as granite, concrete, pavement, and ice (Ref 2). The major problem encountered when cutting hard material is excessive wear and breakage of the mining bit cutter teeth. When cutting hard material, disc saws must be driven at high speeds; as much as 350 to 1,000 fpm tip speeds are required to cut through rock and frozen gravel. High-speed discs are driven from their central hub and cannot trench deeper than their wheel radius – one disadvantage with disc saws. The current state-of-the-art trenches excavated using the disc saw are 40 inches deep by 12 inches wide. If

deeper trenches are required of the nearshore trencher using a disc saw, a new wheel would either have to be installed for each depth range, or an excessively large wheel would have to be permanently installed on the trencher; even for shallow trenches. A 15-foot-deep trench, for example, would require a wheel 35 feet in diameter. For such a large diameter, it is estimated that a 2-inch-thick wheel would weigh approximately 78,000 pounds.

2.3.2 Bucket-Type Trencher

Bucket-type trenchers are primarily used for trenching in soils. Figure 2.3 shows the largest bucket trencher found in this state-of-the-art survey. It has the capability of cutting a trench 12-1/2 feet deep by 18 inches wide. The wheel is approximately 20 feet in diameter, and breaks into two halves for shipping. A crane is required to assemble the 20,000-pound wheel. It should be noted in Figure 2.3 that this wheel is not driven through a central hub as is the case with the disc saw. Instead, a pinion gear drives the wheel through a circumferential rack on the rim; thus, the trencher can trench deeper than its radius. Because the rim rack runs into the trench and through the soil, however, a close tolerance cannot be held on the gears. Both the support rollers and the rack gear teeth operate in dirt, and therefore must be loose fitting, thus requiring that the wheel be driven at slow speeds. Manufacturers of this machine say that it will dig some corals with carbide tip attachments but will not cut rock (possibly due to its slower cutting speed). The trencher is powered by two diesel engines totaling 1,000 hp.

Other manufacturers produce bucket-type trenchers with standard trench capabilities up to 9 feet deep by 72 inches wide. The disadvantage of using bucket trenchers for the nearshore application is their limitation to excavation of soils. Specific energies for these machines average 10.9×10^3 in.-lb/in.^{3}.

2.3.3 Ladder Trencher

The ladder trencher operates similar to a chain saw; Figure 2.4 shows one mounted to the rear of a D-9 caterpillar tractor. Carbide mining cutter bits, mounted on the chain lengths, are driven into the trench to cut the rock. The big advantage of the ladder trencher over the disc saw is its versatility; varying both trench width and depth is relatively easy. One manufacturer's heaviest ladder trencher can dig a standard trench as narrow as 10 inches. However, with the addition of bolted-on base plates, the bits are spaced further apart allowing the trencher to cut 3-foot-wide trenches. To increase trench depth, a longer boom can be attached and chain added piece by piece.

Ladder trenchers are still relatively new in design, but their use is steadily increasing. It was found that by using rock cutting bits and speeding up the chain, many of the early problems encountered with trenching in hard material were minimized. Chain drives of 1,000 fpm or more are now being used successfully to cut rocks. For heavier jobs, the common beam/pulley booms are replaced with solid booms, as is the case for the machine shown in Figure 2.4. Designed for cutting into permafrost, this machine (called the "Roc-Saw") requires 1,000 hp and uses specially designed chain, cutter bits, and boom. The cutter is 14 feet long by 18 inches wide. Standard trench depth is 6 feet in frozen gravel. However, it is capable of cutting 15 feet deep with an extension boom. These machines, like the disc saws, use carbide-tipped cutter bits capable of excavating material up to 20,000 psi compressive strength. These cutter bits, however, are subject to high wear rates and breakage due to side loads. Cutter tip speed is about 800 fpm. Typical specific energies for these machines average 3.8×10^3 in.-lb/in.^{3}.

Cutterhead dredges, tunnel boring machines, and mining machines are included in this group and are all specialized adaptations of rotating machinery. They all use cutter bits to crush the rock's surface.

2.3.4 Mechanical Drag Bit Cutter Teeth

A majority of the mechanical machines use carbide drag bits for cutting rock. A major weakness of drag-bit trenchers when cutting hard rock and frozen gravel is that the drag bits must be constantly replaced due to excessive wear and breakage. In some cases, carbide bits can be ground down, resharpened, and used again. Replacement of drag bits is expensive and time-consuming. For a nearshore trencher, bit replacement would be conducted underwater by divers, greatly increasing the degree of difficulty. In one trenching experiment (Ref 15), the average life expectancy for cutter bits was 3 to 4 hours of trenching time. For every 8-hour day, 3 hours were spent replacing cutter bits.

Large heavy-duty cutter bits can cost as much as $15 each. An 11-foot ladder trencher (designed to trench a 9-foot deep trench) contains about 90 cutter bits. To replace a complete set of these bits would cost $1,400. Both cutter bits and chains are consumable items, and their life expectancy depends on the material being cut and the speed the trencher is cutting.

Up to now, the most common and widely used cutter bit has been the mining bullet-type rock bit (Figure 2.5a). Bullet bits are well-adapted to cutting along their axes. They are, however, poorly designed for taking the side loads required for trenching. In theory, bullet bits are designed to rotate in their mounting blocks while cutting, making them self-sharpening. In practice, however, these bits jam in their blocks and do not rotate. Mellor (Ref 2) tested a disc saw and found that wear and breakage of bullet bits averaged four teeth per cubic foot of excavated frozen ground. Cutting frozen gravel was found to be tougher than cutting reinforced concrete.

In a later experiment, Mellor replaced 130 bullet rock teeth with 60 Hoy bayonet teeth (Figure 2.5b). Wear life on the Hoy teeth exceeded that of the bullet teeth by more than a factor of ten. However, this still meant that the expected wear rate of the Hoy teeth in frozen gravel was 0.4 teeth per cubic foot of excavated material. Mellor suggests that trenching operating costs would be dominated by tooth wear costs.

Vermeer Manufacturing Company (Ref 16) indicated that improvements have been made to the bullet-type rock teeth since the Mellor tests. Vermeer has done its own study and testing of the Hoy tooth, as well as the improved bullet tooth. The study indicated that Hoy teeth showed promise for cutting hard rock and frozen gravel and have been used successfully on both disc saws and ladder-type trenchers. They are about five times as large as the bullet teeth so they do not tend to break as easily when side-loaded. However, they are difficult to mount, and the mounting plate is so large that it usually drags in the side of the trench. The Hoy teeth tend to cut more with brute force and require much more horsepower than bullet teeth. They are not self-sharpening so cutting efficiency goes down and horsepower requirements go up as the tooth wears down.

The improved bullet-type bits have a stronger shank than the old bits and, thus, resist breakage from side loads. They are self-sharpening (when not jammed), so that the horsepower requirement does not go up as the tooth wears. Vermeer has found that the most versatile trencher for cutting rock, coral, and ice is a ladder-type trencher, using the improved bullet-type teeth with the cutters run at 500 to 800 surface fpm. A significant consideration when adapting disc saws and ladder trenchers to cut hard material is to design and build more durable cutting bits. Abrasion of the bit relief face presents the major wear problem. When designing bits, the two factors that must be considered are:

(1) The bits should be made as large as possible for adequate strength

(2) The bits should have properly designed cutting tips oriented and supported so that the resultant cutting force is directly into the work.

Three types of heavy-duty carbide-tipped cutters are shown in Figure 2.6. These cutters are designed with enlarged carbide inserts for cutting into hard material. They are also designed to resist side loading and to conduct the heat away from the carbide when cutting.

In Figure 2.6, the necessary relief angle or clearance angle is shown as angle β_2. From Reference 17, the actual relief angle is defined as:

$$\beta_2 = \beta'_2 + 5^o \tag{3}$$

where β'_2 = kinematic relief angle

For an up-cutting tool, as is the case for disc saws and ladder trenchers,

$$\beta'_2 = \phi - \tan^{-1} \frac{\sin \phi}{\cos \phi + (U/U_t)} \tag{4}$$

where ϕ = cutter bar angle

U/U_t = ratio of trencher advance rate to cutter tool speed

Typical U/U_t ratios range from 1×10^{-3} to 5×10^{-3}. For a cutter bar angle $\phi = 60$ degrees , β_2 varies from 0.5 degree to 0.2 degree; therefore, the actual relief angle should be 5 to 6 degrees for all trenching requirements. Mellor suggests that β_2 is related to the angle of wear flats that develop on the tip of the tool; in principle, there may be possibilities of resharpening the cutter tip by intermittent changes of ϕ and U/U_t.

The tool chipping depth ℓ, defined in Reference 17 and shown in Figure 2.6, is given as:

$$\ell = U/U_t \; S \sin \phi \tag{5}$$

where S = linear spacing between tracking cutter bits

The value S, along with ϕ and U/U_t, should be chosen so that ℓ is large in relation to the "sharpness"* of the cutter, but less than the effective working length of the carbide tip. Typical chipping depths for terrestrial machines range from 0.5 inch for coal saws to 0.02 inch for rock cutters.

*The sharpness of the cutter is characterized by the tool tip radius.

2.4 MECHANICAL PERCUSSIVE SYSTEMS

Percussive tools include impact breakers, percussive drills, and rotary impact drills. These devices develop very high normal-indentation forces to the rock's surface to break it. Impact energy is about 300 ft-lb. As a result, these tools are primarily used on jobs where it is impractical to consider cutting with the parallel-motion drag bit. The major disadvantage with percussive systems is that their efficiencies are poor: specific energies are relatively high – about 1×10^5 in.-lb/in.^{3}.

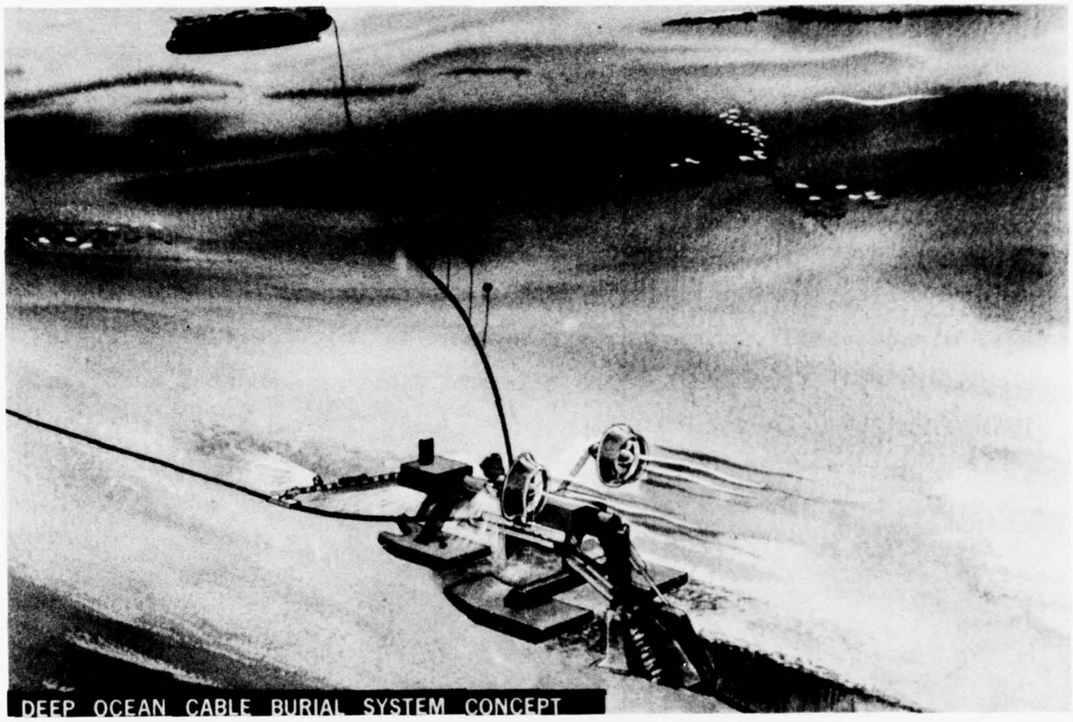


Figure 2.1. Deep ocean cable burial system concept.

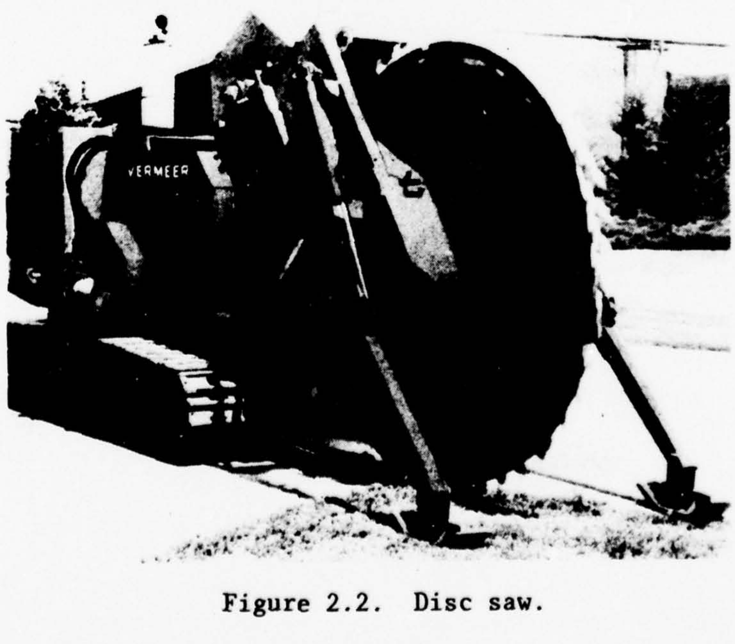


Figure 2.2. Disc saw.

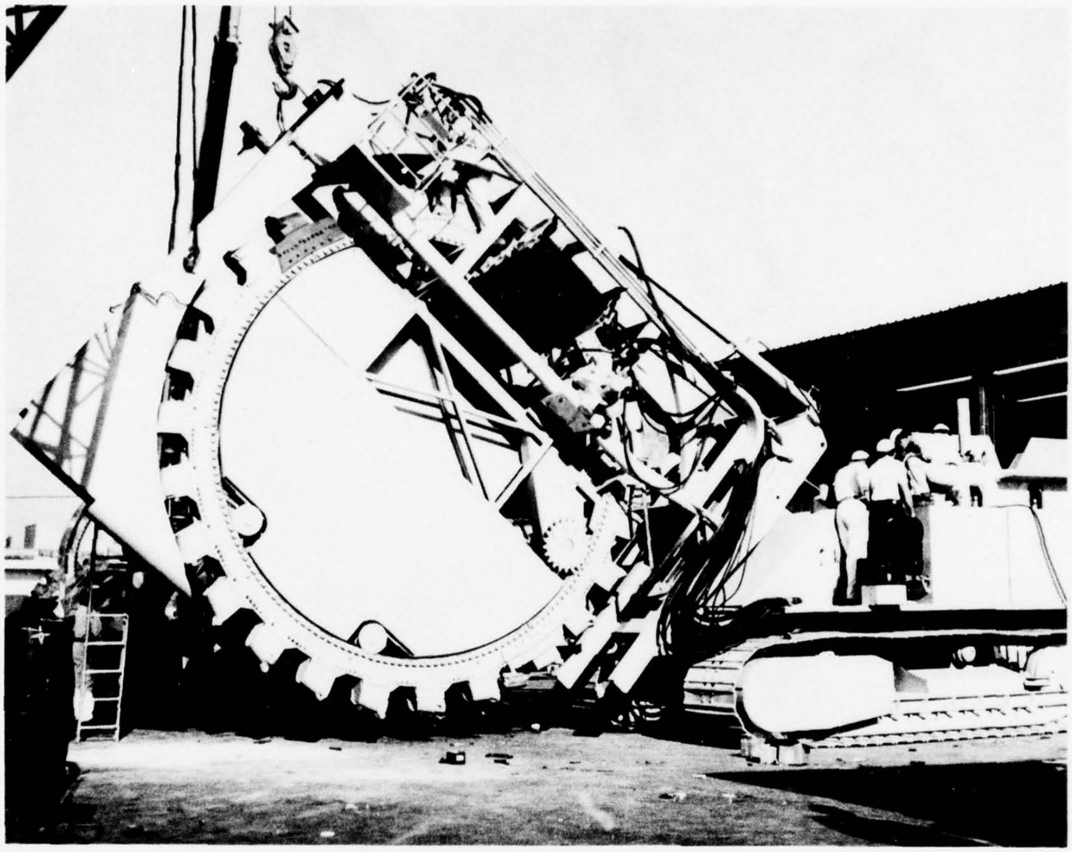


Figure 2.3. Bucket trencher.

Figure 2.4. Bortun Co. ladder trencher.

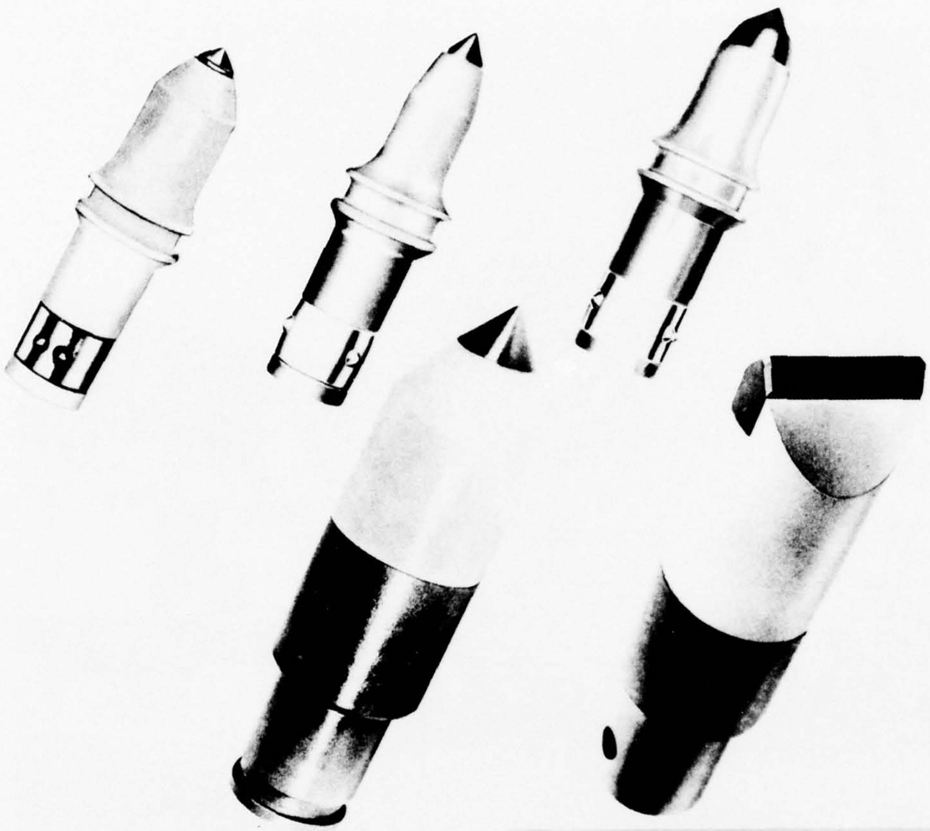


Figure 2.5a. Bullet rock teeth.

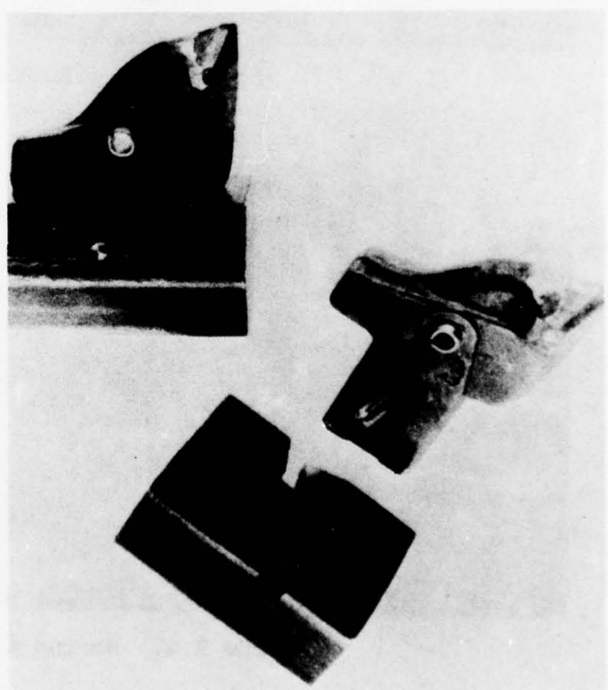
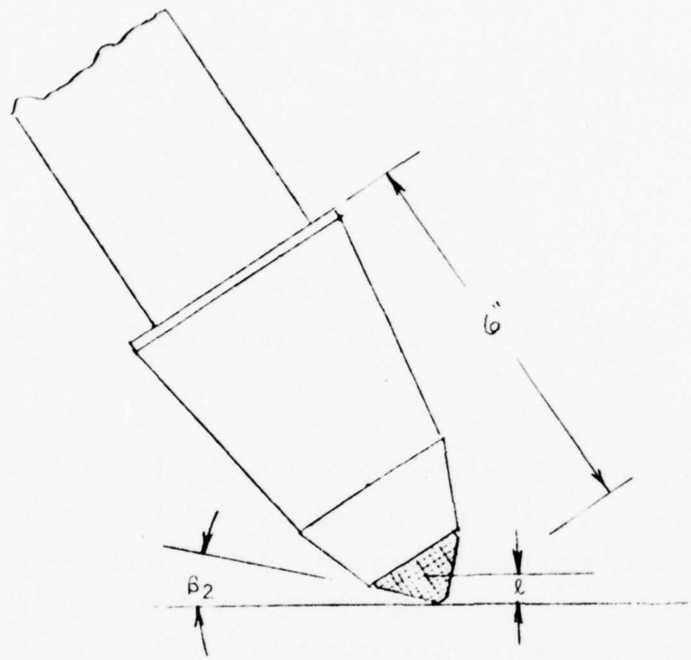
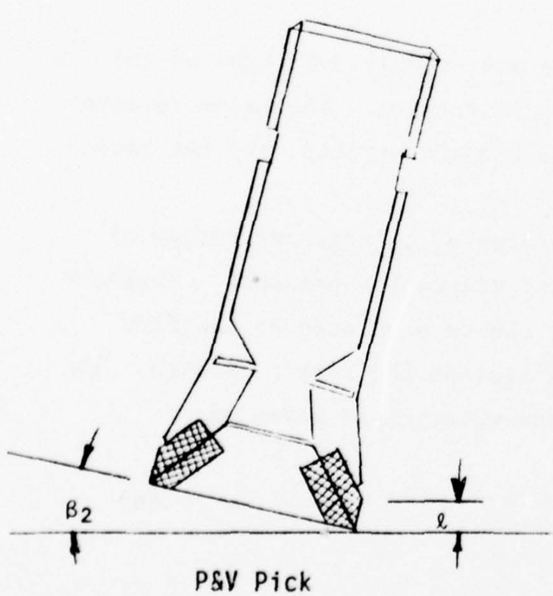


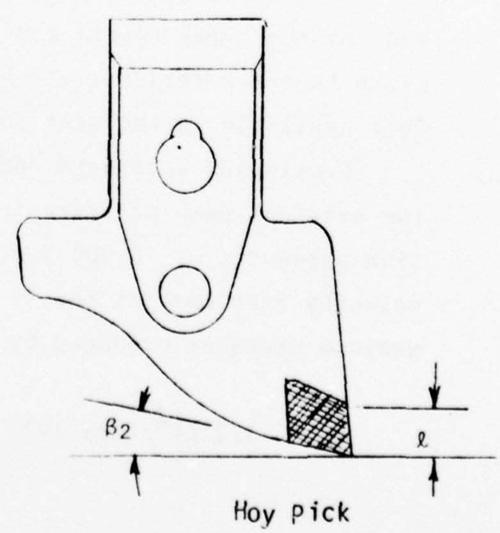
Figure 2.5b. Hoy teeth.



BorTun Co. Bullet Bit



P&V Pick



Hoy Pick

Figure 2.6. Carbide drag bits.

CHAPTER 3
WATERJETS AND HYBRIDS

There are three basic types of waterjet cutting mechanisms – continuous jets, pulsed jets, and cavitating jets – all of which use high-pressure water to mechanically induce high stresses in the rock. Reference 18 contains a complete bibliography compiled in 1973 by the British Hydromechanical Research Association on the subject of waterjet cutting technology.

3.1 CONTINUOUS WATERJETS

Continuous waterjets are by far the most widely used type of jet and, of the three types, are the easiest to control. The major advancements in the waterjet field have been on continuous jets, and the hardware available is the most advanced.

Continuous waterjets operate by recovering a large percentage of the original pump pressure in the form of stagnation pressure. Stagnation pressures of 20,000 to 125,000 psi can be developed as the flow velocity from the jet nozzle is stopped against the rock's surface. The maximum pressure produced by a continuous waterjet is given as:

$$P = 1/2\ \rho V^2 \text{ (Ref 19)} \qquad (6)$$

where P = pressure at the rock's surface

ρ = density of the jet's fluid

V = jet velocity

According to Equation 6, the pressure is proportional to the jet velocity squared; and the velocity, of course, decreases with increasing standoff distances from the nozzle. In addition, continuous jet attenuation is considerably greater under water than in air and is proportional to the standoff distance (Ref 20). This attenuation is caused by high power absorption in the form of heat, turbulence, and noise in the surrounding water. The main disadvantage of using continuous waterjets for trenching in rock is the requirement for large amounts of horsepower and for very high specific energies. On tests conducted by Labus (Ref 41), specific energies calculated for granite, limestone, and sandstone averaged 10^6 in.-lb/in.^{3}, as compared to 10^3 in.-lb/in.^{3} for mechanical trenchers.

Extrapolating from the specific energy calculations, to cut a trench 10 inches wide by 30 inches deep at 0.5 fpm in 6,000-psi rock (coral) using a continuous waterjet would require over 6,000 hp. This indicates that the manner in which the energy is transmitted to the rock is extremely inefficient. It is also estimated that high-pressure water (in excess of 60,000 psi) at the rock's surface is required for cutting (Ref 21). Off-the-shelf hardware (such as pumps, intensifiers, and hoses) are not reliable at these pressures for protracted operation periods. In addition, small nozzle diameters, required for continuous jets, are easily clogged by contaminated water and may not be suitable for seawater use.

3.2 PULSED WATERJETS

Pulsed waterjets apply force to the rock as a sequence of high frequency water pulses, causing an impact water-hammer effect. These pulses are produced by either intermittently interrupting a continuous

jet stream or by sending out short duration water bursts. They are of short duration but of high power intensity. Jet pressures range from 40,000 to over 650,000 psi (Ref 22).

The pressure at the rock surface produced by pulsed jets is given as:

$$P = \rho C V \quad \text{(Ref 19)} \tag{7}$$

where P = pressure at the rock's surface

ρ = density of the jet fluid

C = speed of sound in the jet fluid

V = jet velocity

The pressure in Equation 7 is directly proportional to the jet velocity; however, the speed of sound, C, acts as an amplification factor. Pulsed jets are more efficient than continuous jets. They have slightly lower specific energies than continuous jets (on the order of 10^5 in.-lb/in.^{3}) and, therefore, require slightly less horsepower than continuous jets. The main disadvantage to using pulsed jets for rock trenching is that they produce uncontrolled rock breakage. Increasing the pulse rate increases the control over the jet but, at the same time, increases the power requirement. In addition, the dynamics of the pulsed jet dictates a more complex pump or intensifier design.

Tests performed by Nebeker and Rodriguez and reported in Reference 20, using pulsed jets on granite, limestone, and sandstone found that the water-hammer effect was most effective on granite. They related this to the assumption that different strength rocks have different excavation mechanisms. The high stresses produced by the percussive impact of the pulsed jet promote brittle fracture; hence, the effective cutting rate on hard granite. However, on porous rocks, the primary excavation mechanism may be from erosion of the surface grains resulting from friction of the water, rather than brittle fracture. Thus, the pulsed jet is not as efficient on these rocks.

3.3 CAVITATING WATERJETS

For years, designers of high-speed hydrodynamic systems have tried to minimize the damaging erosion effects of cavitation. The collapse of bubbles at or near solid boundaries is a serious problem in hydrofoil, pump, and propeller systems. Cavitating waterjets use this phenomenon of collapsing bubbles to produce extremely high pressures at the surface of the rock. The cavitating waterjet nozzle is designed to produce flow with regions of pressures below the local vapor pressure. This low pressure area within the flow causes vapor bubbles to grow and form cavities. The cavities then collapse on the rock's surface due to the local stagnation pressure. The high-pressure forces caused by the collapse of these cavities act like a pressure amplifier, producing local pressures from 60,000 psi to hundreds of thousands of psi.

The main differences between cavitation cutting and continuous flow jet cutting are:

(1) Continuous waterjets rely on the stagnation pressure alone to stress the rock; therefore, trying to achieve maximum pressure by maintaining a coherent or highly concentrated flow.

(2) Cavitation waterjets, being noncoherent flow jets, rely on the cavitation phenomenon to amplify the pressure 100 times the stagnation pressure.

Figure 3.1, taken from Reference 23, graphically illustrates the pressure amplification factor produced by cavitation. For continuous jets, shown by the curve on the right of Figure 3.1, the theoretical impact pressure is equal to the pump pressure. For cavitating waterjets, the theoretical impact pressure could be as high as 100 times the pump pressure, depending on the gas content in the vapor cavities. For example, a cavitating waterjet with a gas content of 1/8 and a pump pressure of 2,000 psi can theoretically attain an impact pressure of 80,000 psi. This amplification factor allows use of reliable off-the-

shelf medium pressure pumps and support hardware to produce high-pressure outputs. In addition, tolerances on cavitating waterjet nozzle diameters are less critical than those for continuous jets. As a result, these nozzles are less susceptible to clogging and may, in fact, be adaptable to seawater usage.

One disadvantage of cavitation waterjets is their critical standoff distance. If the jet nozzle is located on either side of the optimum standoff distance (±0.5 inch), the output pressure intensity falls off sharply.

3.4 SIGNIFICANT ADVANCES IN CAVITATING WATERJETS

In recent years significant advances have been made in the design of cavitating waterjets. Optimizing the nozzle design has reduced many inherent problems. Specifically, specific energy and power consumption have been reduced, and standoff distances made less critical. Under contract to the Office of Naval Research, Daedalean Associates in Maryland have been investigating the use of cavitating waterjets for cutting steel. In their investigation, they successfully demonstrated rock cutting with submerged cavitating jets. Specific energies for these tests indicated the cavitation jet was as efficient as the most efficient mechanical trenchers. During Phase I of their investigation, they were able to operate at 4 gpm (jet velocity = 350 to 750 fps) and 7,500 psi pump pressure. The critical standoff distance was 0.45 inch, or approximately 10 nozzle diameters. Early work in cavitating cutting (in the range of 350 fps jet velocity) indicated that the material removal rate was proportional to the jet velocity raised to the sixth power:

$$\dot{Z} \propto V^6 \qquad (8)$$

where $\dot{Z}$ = material removal rate (known as erosion rate)

V = jet velocity

Under the new phase of the investigation, they extended their operation to 15,000-psi pump pressure and 1,250-fps flow. Results showed that the erosion rates were increased significantly and are proportional to the velocity raised to the fourteenth power (Reference 24):

$$\dot{Z} \propto V^{14}$$

In addition, experimental data indicate that the optimum relationship of the velocity power law has not yet been achieved.

Standoff distances were found to be less critical at higher pump operating pressures. Figure 3.2 shows breakthrough times for various standoff distances. Breakthrough time is defined as the time it takes to cut through a 1/4-inch aluminum specimen. The curves indicate that the critical standoff distance is increased with increasing pump pressures. For example, at a pump pressure of 12,000 psi, the optimum standoff range is between 0.5 and 0.95 inch. At these higher pressures, the cutting rate was found to be relatively constant over a wider range of standoff distances.

During Phase II of their investigation, Daedalean Associates were able to cut a 2-1/2-inch-diameter hole, 6 inches deep in 30,000-psi granite in 1 minute. Total power input was less than 20 hp, which gives a specific energy of 2.05×10^3 in.-lb/in.^{3}. This number is very competitive with specific energies calculated for mechanical trenching machines. However, it must be pointed out that these tests are strictly small-scale laboratory experiments. Caution must be used when scaling up to a machine as large as a trencher without some prototype data.

If determined a feasible method for trenching in rock, cavitation waterjets have distinct advantages for the nearshore application over mechanical trenchers. The experimental 12,000-psi jet nozzles show absolutely no signs of wear because the actual cavitation phenomenon occurs downstream of the nozzle. This is a significant advantage over mechanical trenchers. There are no moving parts at the cutter/trench interface and no signs of wear at the nozzle; therefore, there are no

cutter bits to replace or resharpen. In the case of an underwater trencher, this means less required diver support time. In addition, since the working fluid is water, any system leaks or spills would not affect the environment. If filtered seawater could be pumped through the jets, the working fluid reservoir would be unlimited. Another advantage of cavitation jets is that they do not appear to be power-limited as drag bit trenchers are. In the case of carbide bits, there is a power density factor that limits the amount of power applied to the cutters. Any power applied in excess of the power density factor would only serve to break the bits. Cavitation jets do not have this limitation: the more power input to the nozzle, the more power output applied to the rock.

3.5 HYBRID SYSTEMS

3.5.1 FARE Ripper

Some cutting experiments have been performed by combining different existing methods into one in hope of improving trenching efficiencies. One such study was performed on the Fuel/Air Repetitive Explosions (FARE) ripper (Ref 25). The system, shown in Figure 3.3, was developed by Southwest Research Institute.

Standard ripping capabilities are determined by tractor weight and installed power. The FARE ripper system increases the cutting efficiency (and thereby decreasing the draw-bar requirements) by fragmenting the rock with high-pressure gas. As shown in Figure 3.3, a combustion chamber is charged with a mixture of compressed air and hydrocarbon fuel. As soon as the ripper tooth begins to penetrate the rock, the mixture is ignited with a spark plug. This causes high-pressure gas to be released into the bedding planes of the rock to be fractured.

Esco Corporation of Oregon has taken the FARE ripper system one step further. In place of the combustion chamber, they are investigating

using a high-pressure waterjet to assist in fracturing the rock. This ripper technique is experimental, and investigations are still being conducted.

3.5.2 Coal Plow

Moodie (Ref 26) experimented with combining a conventional coal plow with pulsed waterjets. Figure 3.4 shows the plow wedge fitted with the high-pressure jets. During tests with the plow, it was demonstrated that the waterjet assisted in cutting and breaking the coal, causing a reduction in the normal plow draw-bar pull. The plow incorporates eight waterjets operating at 50,000 psi each. The average specific energy attained during these tests was calculated to be 3.2×10^3 in.-lb/in.^{3}. This efficiency is comparable to coal mining equipment; however, full scale excavators of this type are still limited to cutting softer materials (such as coal with $\delta = 3{,}000$ psi).

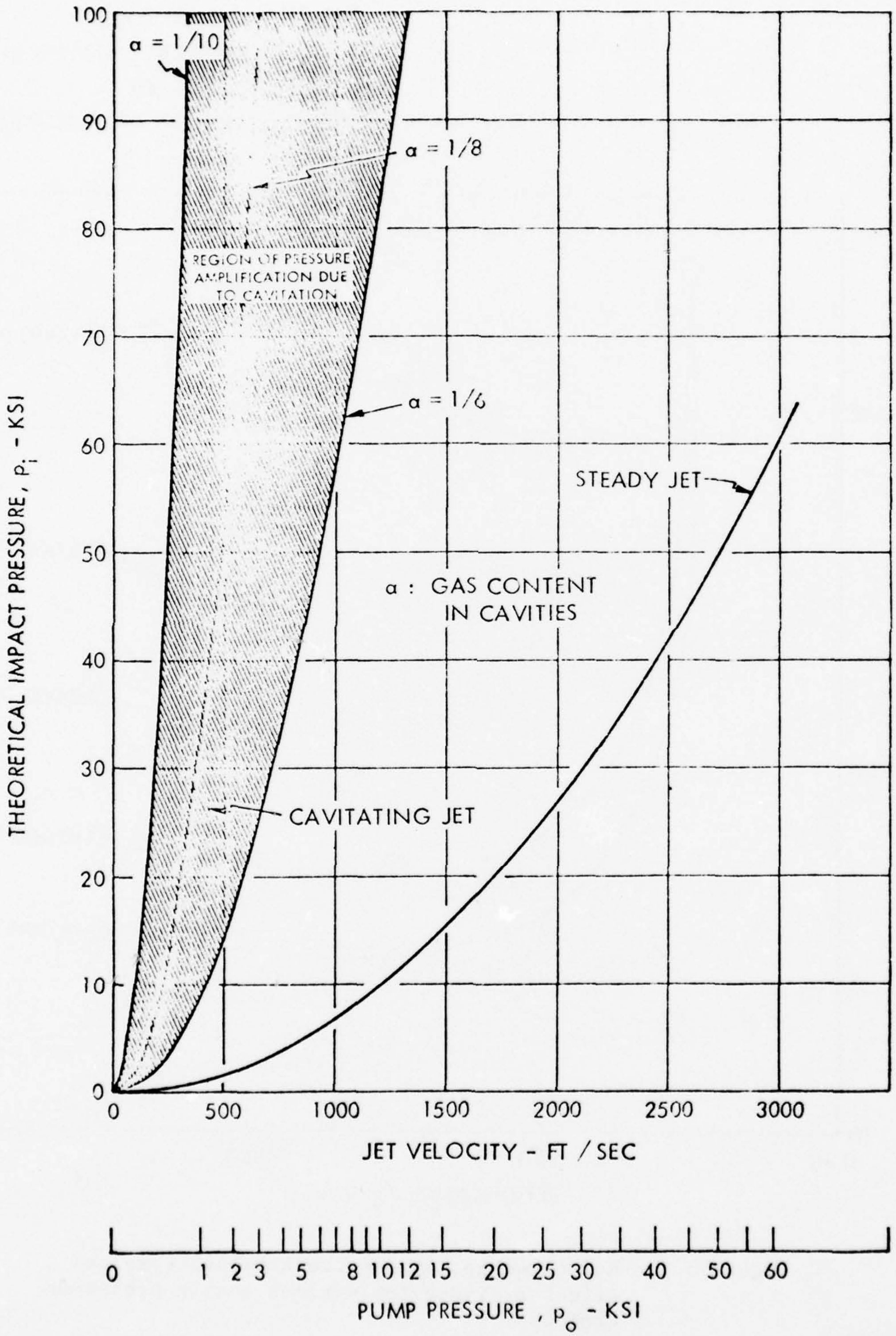


Figure 3.1. Theoretical comparison of cavitating and steady waterjets.

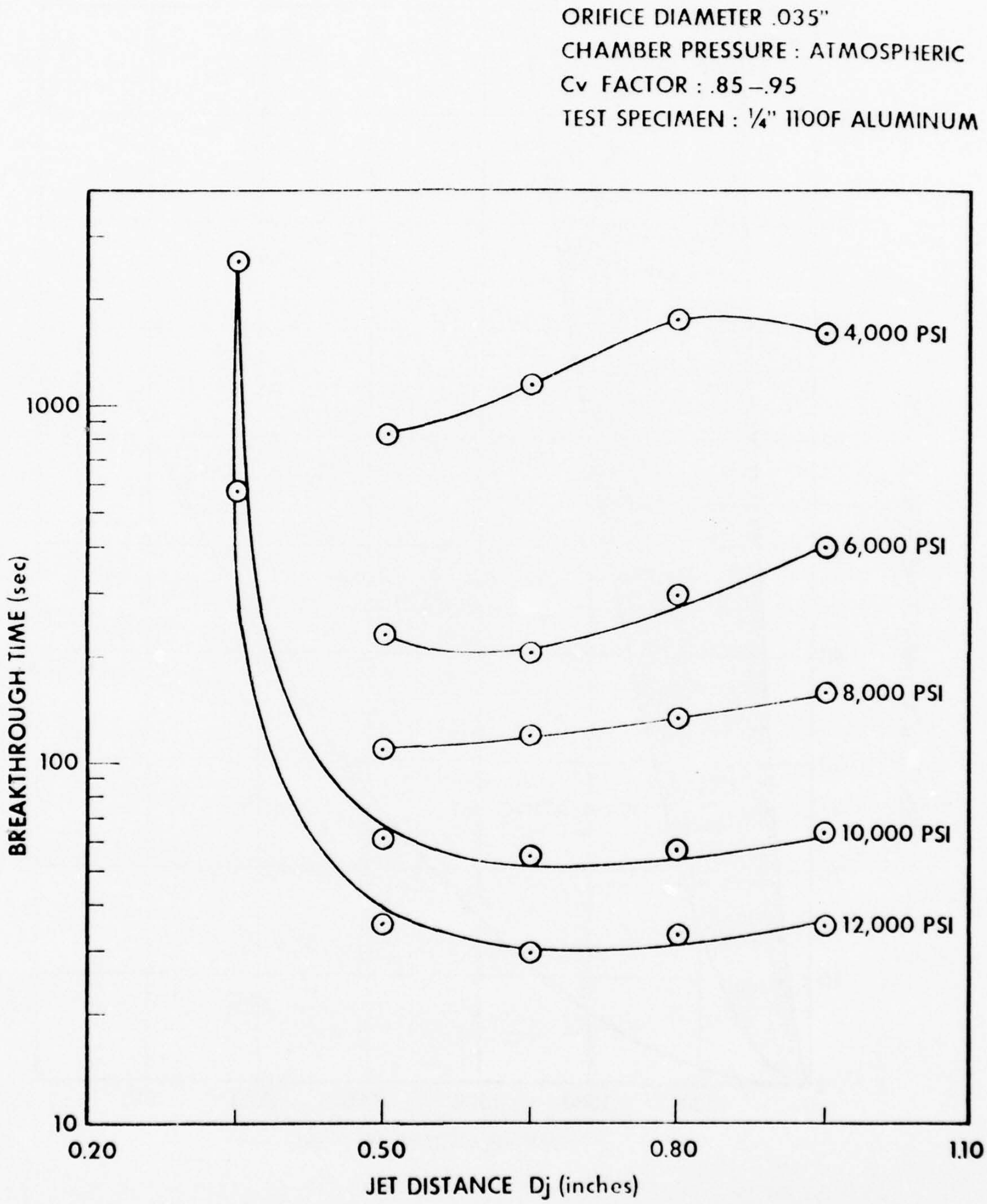


Figure 3.2. Relationship between breakthrough time and offset distance for various nozzle pressures. (Ref 25).

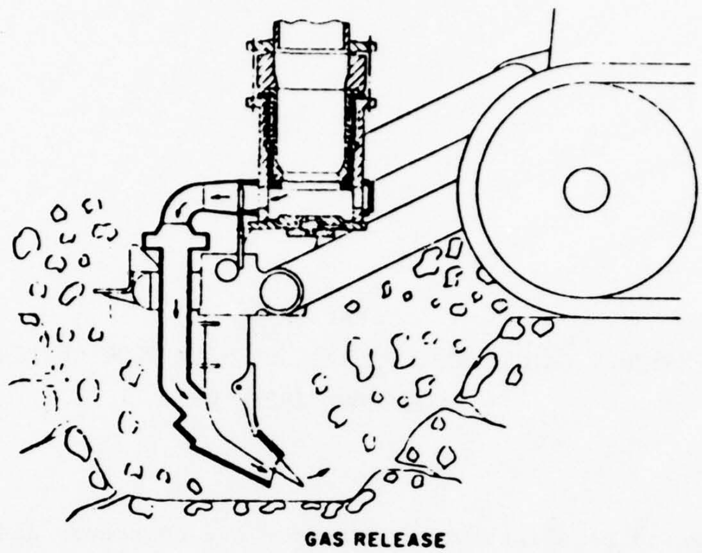


Figure 3.3. FARE ripper.

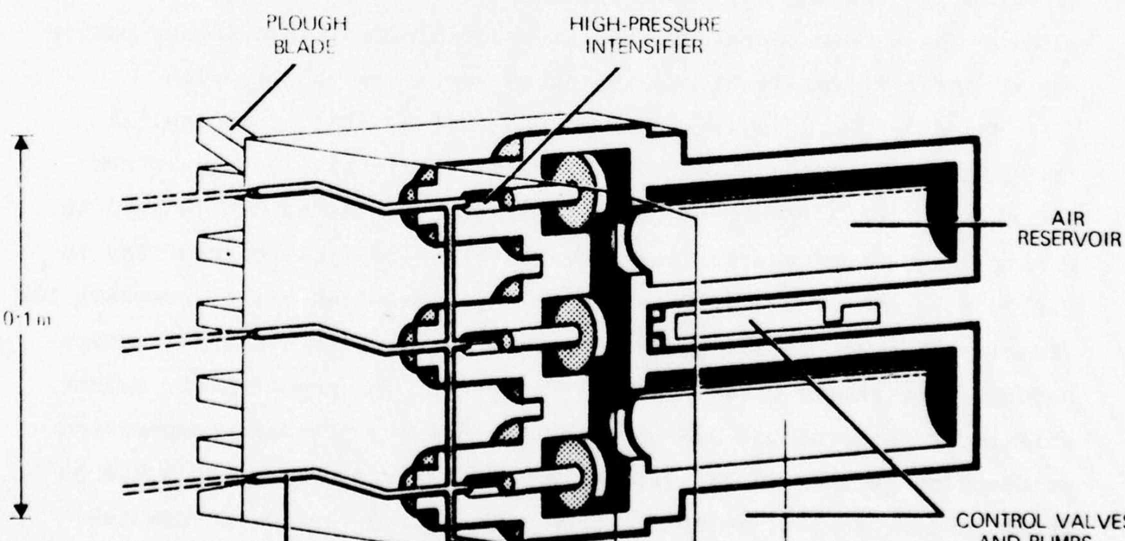


Figure 3.4. Plough wedge fitted with means for providing high-pressure jets to weaken coal ahead of plow blades.

CHAPTER 4

EXPERIENCE GAINED WITH PACIFIC MISSILE TEST CENTER (PMTC) NEARSHORE TRENCHER

Cables and pipelines which traverse the nearshore and surfzone regions often require stabilization to prevent damage from hydrodynamic forces and anchor snags. Historically, a number of techniques have been used, including split pipe (for cables), concrete and chain, trenches produced by blasting and dredging, and fasteners grouted into the seafloor. These techniques have not always exhibited satisfactory performance, and the installation/maintenance costs are usually high.

Based on previous work done at CEL (Ref 27, 28), a mechanical trenching machine appeared to be a viable alternative for nearshore protection. As a result of these studies, PMTC tasked CEL in 1975 to modify a land trencher for use under water. The final concept was to modify a Vermeer T-600 7-foot-diameter disc saw trencher by removing the diesel engine and transmission and replacing it with hydraulic motors powered by a remote diesel-hydraulic source. The remote power source utilized a turbocharged 220-hp diesel to drive a pressure-compensated piston pump capable of delivering 105 gpm at pressures up to 5,000 psi. Three hundred feet of hydraulic hose transmitted the power from the source to the trencher. The disc saw, 7 feet in diameter, was capable of cutting a trench 31 inches deep by 6 inches wide.

In August 1975, the modified trencher was deployed to Midway Island to be used during a cable-installation operation. Technical problems were encountered during the 30-day operation which reduced the trencher performance to considerably less than originally projected. Major

problems included inadequate control of the fluid power distribution, jamming of the track drive system due to sand buildup, and rupturing of the hydraulic hoses. A total of 600 feet of trench was cut in a protected lagoon with bottom conditions ranging from sand to solid coral. Even though the trencher was not able to bury all the cable as planned, it was successful in demonstrating that the concept of mechanical trenching on the seafloor is feasible.

Based on the experience gained during the Midway trenching operation, PMTC rebuilt the Vermeer trencher for use on a cable installation in the Hawaii area. This second-generation underwater trencher (shown in Figure 4.1) utilized the same chassis, track drive system, and disc saw used at Midway. The hydraulic system, power source, and operator controls were redesigned. The new hydraulic system utilized separate flow control valves for each track and cutter wheel motor, allowing much better control of the power distribution to the various fluid power circuits.

In early September 1976, the trencher was shipped to the Pacific Missile Range Facility, Barking Sands, Kauai, to provide trenches for three list 5 (double-armored) SD coaxial cables. During 3 weeks of operation, approximately 400 feet of trench was cut through hard beach rock before mechanical failures caused cancellation of the trenching operation.

In general, this trencher appeared to operate better than its Midway predecessor. The major problems at Midway seemed to be solved (i.e., hydraulic hoses rupturing, inadequate control of the fluid power distribution, and jamming of the track drive system). The problems which caused the trencher to produce less than the desired results at Kauai were primarily a result of the environmental effects on various mechanical systems. These are described in the following paragraphs.

4.1 POWER SYSTEM

Power for the PMTC trencher was supplied by a diesel-driven, pressure-compensated, variable flow pump. The maximum flow rate was limited by the size of the pump suction filters. Above 140 gpm, enough of a pressure drop occurred through the filters that the pump began to cavitate. While operating the trencher on land, the maximum pressure was limited to 2,000 psi because of overheating of the hydraulic oil. Even when held to 2,000 psi, the power source had to be periodically shut down to allow the oil to cool off.

Because of these power limiting factors (plus the power loss through the 300 feet of umbilical hydraulic hoses), it is estimated that, while operating continuously on shore, less than 50 hp was delivered to the trencher. It is estimated that during submerged operation sufficient cooling would be provided by the seawater to allow the power to be increased by at least 100%.

Additional problems experienced with the power system included:

(1) Pressure oscillations at the pump, caused by the accumulator effect of the high pressure hose and the slow response time of the pressure compensation system. These fluctuations were often in the range of 2,000 psi and lasted for several minutes before they damped out.

(2) The heavy weight of the hydraulic hose posed a potential hazard to people working with it on the beach.

4.2 TRENCHING SYSTEM

A 31-inch-deep by 6-inch-wide trench, shown in Figure 4.2, was cut by the 7-foot-diameter disc saw. The maximum continuous rotational speed developed by the saw was about 23 rpm (approximately 500 surface fpm), which is only about one-half the speed required for rock cutting. The material trenched on the beach ranged from soft sandstone to a hard cementitious sandstone. Trencher advance rates varied from 2 fpm to

about 0.1 fpm respectively. Except for the relatively slow advance rate, the trenching mechanism seemed to work well. Two problems were observed:

(1) While attempting to cut a 50-foot-long curved section of trench in the harder rock, 28 cutting teeth were broken due to the high side loads against the side of the trench. Figure 4.3 shows the broken teeth on the cutter rim. Note that in some cases, the carbide tips are completely missing from the bullet-shaped bits.

(2) Sand buildup in the cutter wheel drive sprocket caused the drive chain to stretch and jump off the sprocket several times. This ultimately led to the failure of the triple roller chain (Figure 4.4).

In addition, the conveyor belt, normally used to remove excavated material from the trench on terrestrial machines, proved to be inadequate under water. Water currents keep the cut material in suspension, making the conveyor useless.

4.3 TRAFFICABILITY

The track system was not changed from that used at Midway with the exception of using higher torque drive motors; the problems of low ground clearance and poor obstacle negotiation still existed. Even with the added power to the track drive, it was impossible for the trencher to negotiate any vertical discontinuity greater than 6 inches in height.

The combination of low ground clearance and high bearing load from the tracks presented problems in developing sufficient draw-bar pull in the surfzone. While trenching in the surfzone, the tracks sank into the sand until the trencher bottomed out on its skid pan, thus stalling the trencher wheel. The combination of the rising surf and vibration from the cutter disc liquified the sand under the trencher, causing it to sink even further (Figures 4.5 and 4.6). The trencher then had to be raised, using the cutter wheel and scraper blade, to allow sand to fill back in under the tracks.

The rigid track suspension also posed some problems. On irregular surfaces, one or the other of the tracks was usually suspended for most of its length. This reduction in contact area resulted in increased track slippage.

4.4 ANALYSIS OF THE PMTC TRENCHER OPERATIONS AT BARKING SANDS

Even though this trencher was an improvement over the one used at Midway, its capabilities were still severely limited for use in the ocean. The following performance parameters were estimated for the PMTC trencher, based on data gathered at Barking Sands during September 1976. Hydraulic line losses and power distribution percentage parameters used in the following calculations were assumed since they were not monitored in the field. These assumptions were based on 80% of the total trencher power distributed to the trenching mechanism and 20% of the total power distributed to the track drives.

(1) Rock Trenching in Soft Material:

a. 91 hp total provided to the machine

b. 72 hp provided to the cutter disc

c. 0.7 fpm average advance rate

d. 18.7×10^3 in.-lb/in.^{3} specific energy

e. 500-fpm tool speed

(2) Rock Trenching in Harder Material:

a. 58 hp total provided to the machine

b. 46 hp provided to the cutter disc

c. 0.3-fpm average advance rate

d. 28×10^3 in.-lb/in.^{3} specific energy

e. 500-fpm tool speed

Table 3 shows a comparison of the PMTC trencher to its equivalent terrestrial counterpart – the Vermeer T-600 trencher. From the specific energy comparison, it can be seen that the PMTC trencher operates five to eight times less efficiently than the Vermeer T-600. It is estimated that the majority of losses in the PMTC machine are due to track slippage, heat loss in the flow control valves, and line losses in the hydraulic hoses.

The following analysis was performed to determine what the theoretical operating capabilities of the PMTC trencher should have been.

Figure 4.7 shows the theoretical horsepower requirements for a 7-foot-diameter disc cutter trenching 30 inches deep by 6 inches wide. The diagonal lines (1) of Figure 4.7 give the theoretical power requirements for coral and rock trenches based on terrestrial trenching machines. The power density band (2) of Figure 4.7 is the theoretical optimum power (90 hp ±20%) that should be delivered to the cutter disc. More than this amount of power distributed over the cutters would cause excessive cutting forces and damage the cutters, and less than this amount would not be sufficient to allow the cutter bits to "bite" into the rock. Where lines (1) and (2) intersect are the theoretical trenching rates for the various materials:

(1) 1.7 fpm in 20,000-psi rock*

(2) 2.7 fpm in 16,000-psi rock

(3) 5.5 fpm in 6,000-psi coral

Most disc cutters have tool speeds in the range of 100 to 1,000 linear fpm. Low tool speeds are associated with high tool forces but tend to minimize wear rate by keeping the carbide tool temperature

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*There is some question as to whether 20,000-psi rock can be trenched using carbide cutters.

relatively low. High tool speeds are associated with lower tool forces but softening of the carbide bit due to high tip temperatures. However, it is likely that the PMTC trencher can operate at 700 to 1,000 fpm tool speed as long as the seawater acts as an effective coolant to the cutter bits.

The upper limits for traverse speed, U, are defined by lines (3) in Figure 4.7. These are the maximum advance rates possible for tool speeds of 700 fpm and 1,000 fpm and are based on the physical chipping capability of each cutter bit. Line (4) indicates the maximum advance rate for terrestrial trenches operating without cooling to the cutters. This limit might be expected for beach operations prior to entering the surfzone. Tool speeds greater than 700 fpm without cooling are not recommended for hard material.

In summary, the theoretical traverse speeds attainable for a 30-inch-deep by 6-inch-wide trencher with 90 hp delivered to the cutter mechanism are shown in Table 4.

An advance speed of 0.5 fpm has been specified in several NAVFAC documents as the minimum required traverse speed. Experience with the PMTC trencher in the field (traverse speeds of 0.3 fpm in hard rock and 0.7 fpm in softer material) has demonstrated how slow 0.5 fpm really is. For example, the trenching project at Barking Sands, Hawaii, ideally planned to trench and bury four cables 3,000 feet out from the shore. This is a total of 12,000 feet of trench. Assuming a working day of 12 hours each, the optimum expected is 8 hours of trenching and 4 hours of down-time. At a rate of 0.5 fpm, the 12,000 feet of trench would take 50 consecutive 12-hour days (assuming the trencher never breaks down).

Thus, it is advisable to design for a somewhat higher advance rate than the minimum required. In addition, 20% more power should be added to the previous theoretical calculations to include propulsion power and machine losses.

Table 3. Comparison of PMTC Trencher to Vermeer Trencher

Trencher	Horsepower to the Machine	Specific Energy
PMTC	91	18×10^3 to 28×10^3
Vermeer	108	3.5×10^3

Table 4. PMTC Trencher Analysis

Material	Environment	Cutter Tool Speed (fpm)	Advance Rate (fpm)	
			Theoretical	Achieved
Rock (12,000 psi)	dry beach OPS	500	0.5	0.3
	submerged	700 to 1,000	2.7	no data
Coral (6,000 psi)	submerged	1,000	5.5	no data

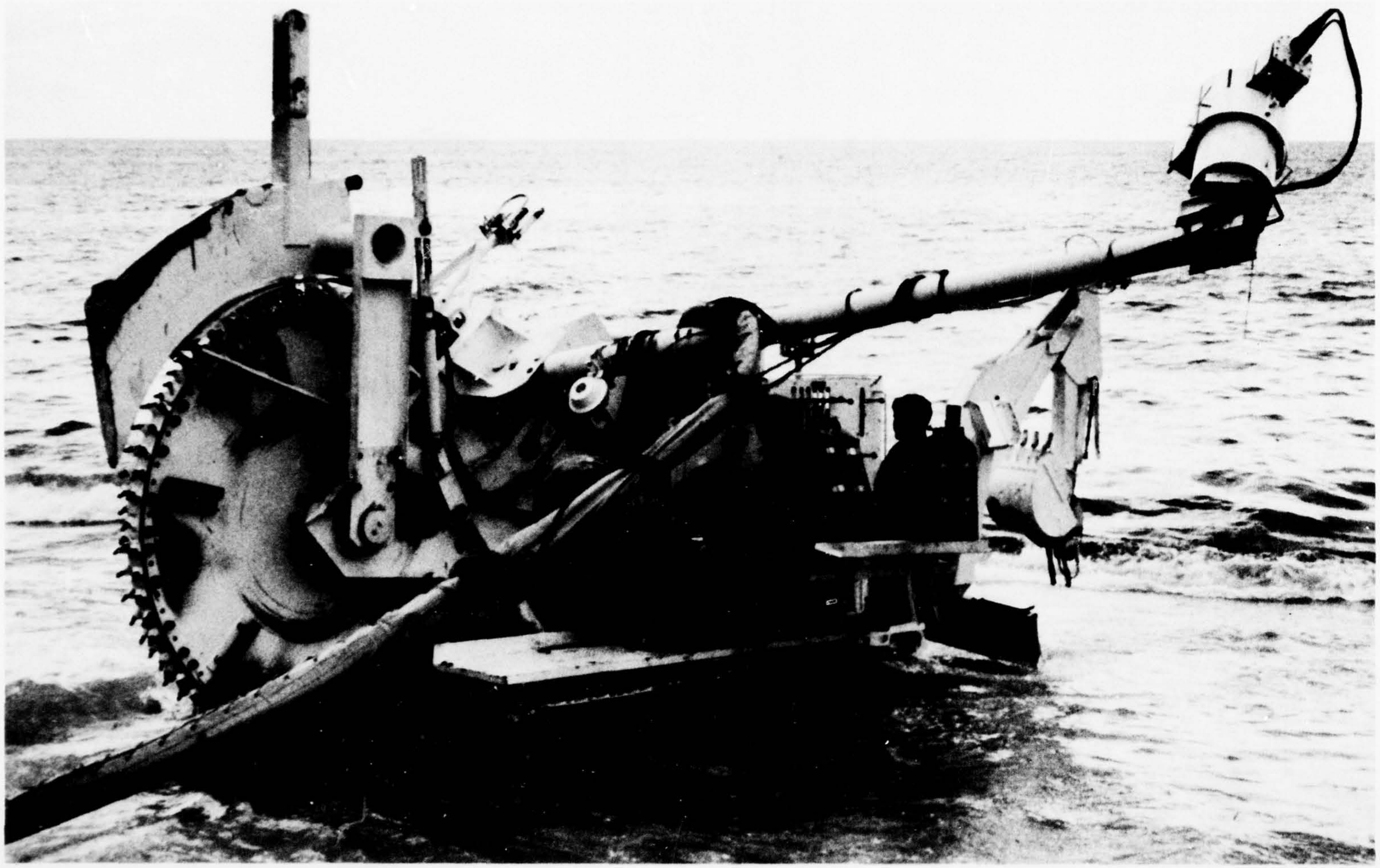

Figure 4.1. PMTC nearshore trencher.

Figure 4.2. Trench at Barking Sands.

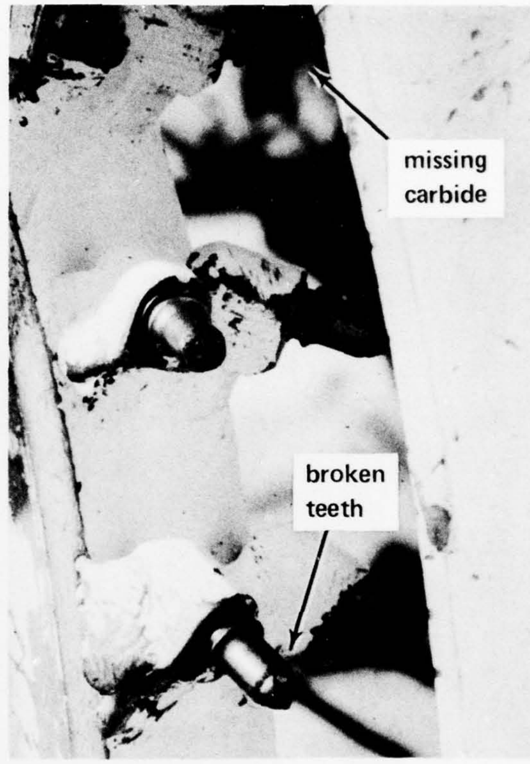

Figure 4.3. Broken carbide bits.

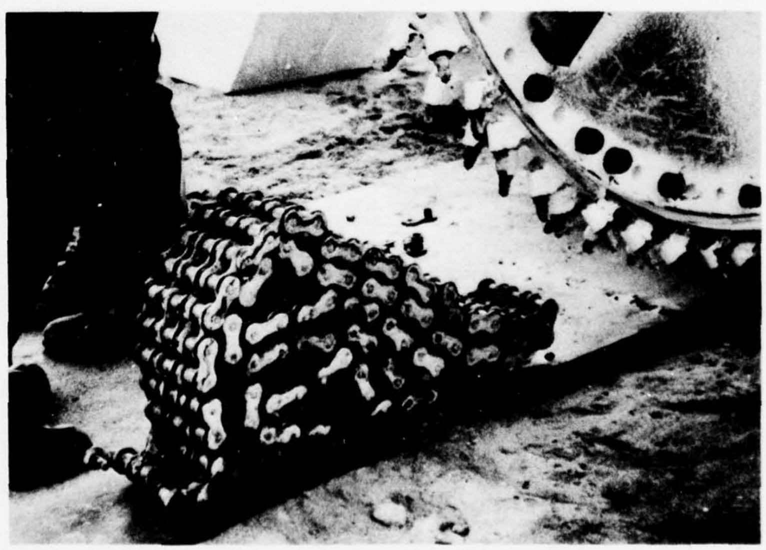

Figure 4.4. Broken drive chain.

Figure 4.5. Trencher in the surf.

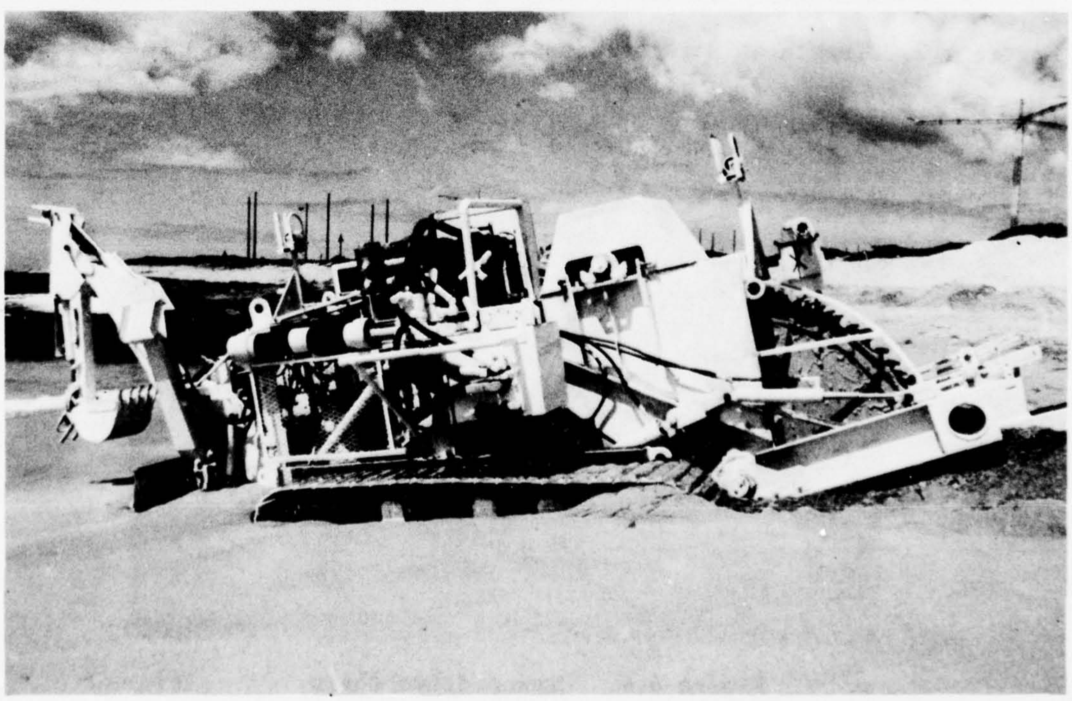

Figure 4.6. Trencher sinking in sand.

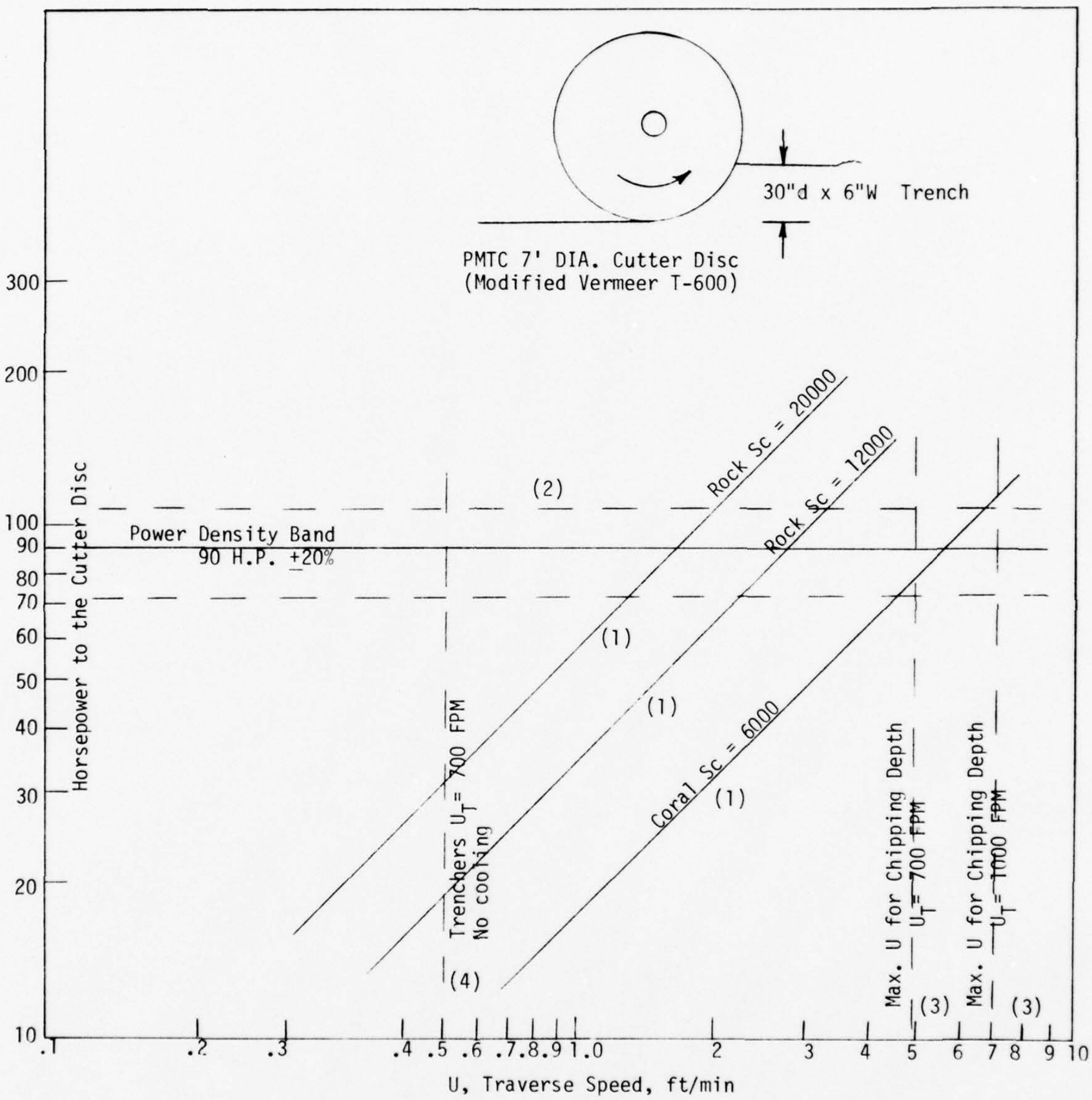

Figure 4.7. Theoretical operating power requirements to the cutter.

CHAPTER 5

REVIEW OF NEW DEVELOPMENTS AND NOVEL EXCAVATION TECHNIQUES

Today, most excavation in hard rock is done by the drill and blast method. Under study, but with large operating energy requirements, are:

(1) Softening rock with chemicals

(2) Weakening rock with lasers

(3) Fracturing rock with heat jets and infrared guns

This chapter contains an overview of these novel techniques. Keep in mind, however, that these techniques are not state-of-the-art for trenching. New developments in rock excavation are being examined constantly, utilizing the four basic methods of excavation discussed earlier:

(1) Mechanically induced stresses

(2) Thermally induced stresses

(3) Fusion and vaporization

(4) Chemical reactions

The latter three methods are all novel techniques in themselves. Mechanical methods are by far the most advanced. Few novel techniques have been tested outside the laboratory (i.e., there are very few full-

scale prototypes), because the novel techniques must compete with the established conventional mechanical excavators, which have undergone many years of development. For example, oil field rotary drills have been used since 1884. Since that time advanced developments have increased their drilling rates 10 to 100 times. Similar improvements would be expected of the novel techniques once they are put into routine commercial use. Many of the following novel techniques discussed here are for rock drills and are taken from Reference 7, but the excavation mechanism is the same for trenching as for drilling. The principles involved are just as applicable.

5.1 MECHANICALLY INDUCED STRESS MACHINES

5.1.1 Pellet Technique

A pellet drill, shown in Figure 5.1 (Ref 29), is essentially a waterjet with abrasive additives. The main difference is that there are two nozzles: a primary and a secondary. Fluid is pumped down through the primary nozzle, producing an aspirator effect. Small steel pellets are inserted down the drill pipe. The aspirator action of the primary nozzle forces the pellets inside the drill where the secondary nozzle accelerates them to 75 fps. The accelerated pellets then strike the rock, fracturing it. The pellets and broken rock are then lifted by the rising fluid to the aspirator opening where four-fifths of the fluid/pellet mixture is recirculated. The remaining one-fifth of the pellets are constantly replaced via the drill pipe. The important advantage to a system such as this is that the pellets, which act like cutter bits in the case of mechanical trenchers, are constantly being replenished. Since the cutting elements are replaced without pulling the drill from the hole, the need to stop the machine for cutter replacement is eliminated. This concept would eliminate the requirement to have divers replace cutter bits, which would normally be the dominating "down-time" factor for mechanical drag bit trenchers.

However, tests performed with the pellet drill show it is very inefficient. Only 4% of the hydraulic power input to the drill is actually transmitted to the pellets. Specific energy based on pellet power output was found to be 1.13×10^6 in.-lb/in.^{3} for limestone.

5.1.2 Implosion Technique

An implosion drill (Ref 7) is shown in Figure 5.2. This drill pumps hollow, hermetically sealed capsules down the drill hole until they implode on impact against the rock surface. The implosion of the capsules sets up high pressure pulses within the rock. The major disadvantage to the implosion system is that it requires 13,000 10-cm spheres per hour, which is cost prohibitive.

5.1.3 Spark Technique

Experiments have been under study to determine suitability of high voltage discharges to produce explosive-like pressure pulses. Figure 5.3 shows a typical spark drill (Ref 7, pp 24-29). These drills set up a powerful electric field which produces a conducting channel of ionized gas between electrodes. Condenser-stored energy then flows through the conducting zone creating a high-temperature plasma, which produces pressures of 10^4 to 10^5 atmospheres in water. The spark discharge system must be submerged in water to work.

The power output of a spark drill is extremely high for short periods (about 1,000,000 hp for 5 to 50 seconds). One of the advantages of the spark drill is that it can have a high output power concentration over a small area and, therefore, it can have high potential excavation rates. For example, a spark drill firing 10 sparks per second with a 4-μF capacitor charged to 70 kV would have an equivalent output of 133 hp. However, total energy requirement is about double that of conventional rock drills due to the inefficient transmission of the energy to the rock. Specific energies are calculated to be 4.6×10^4 to 7.6×10^4 in.-lb/in.^{3} in sedimentary sandstone.

5.1.4 Ultrasonic Technique

An ultrasonic drill, shown in Figure 5.4, has been used successfully to drill extremely hard material such as diamond, ceramic, and rock (Ref 7, pp 44-49). Ultrasonic drills use magnetostrictive cores to vibrate emitters at frequencies of 20 to 30 kc. While in the variable magnetic field, the core expands and contracts with an amplitude of several microns. A resonant tapered horn, located between the magnetostrictive transducer and the cutting tool, causes the vibration to resonate, amplifying it 10 to 100 times. Ultrasonic drills must be used in water. The transfer of energy from the emitter to the water causes cavitation bubbles to form and migrate to the rock surface. The collapse of these cavitation bubbles on the rock forms high implosion stresses. Cavitation from the ultrasonic drill dies out at pressures above 160 feet of seawater. In some tests, hard abrasives are introduced below the tool, where the turbulence caused by cavitation accelerates the abrasives against the rock at high velocities. Data indicate that ultrasonic excavation techniques require large amounts of energy with associated slow drilling rates. Specific energies have been calculated to be

$$2.7 \times 10^6 \text{ to } 2.7 \times 10^7 \text{ in.-lb/in.}^3$$

5.2 THERMALLY INDUCED STRESS MACHINES

The amount of heat necessary to induce thermal stresses in rock must cause the rock to heat up to 750° to $1,100^\circ$F. This threshold causes the rock to spall and degrade.

5.2.1 Jet Piercing Technique

A jet piercing drill is shown in Figure 5.5 (Ref 7, pp 50-53). This drill works by burning a jet of oxygen and fuel oil at 6,000 fps and 5,400°F to spall the rocks. This method can concentrate an extremely large amount of energy, but this method only works on spallable rocks. Limestone, for instance, cannot be excavated by jet piercing because it does not spall. In addition, jet piercing is inefficient (only 15% to 50% of the energy used) due to the combination of poor heat transfer to the rock and high flame speeds. The poor heat transfer for an underwater jet piercing trencher would produce even worse efficiencies. Specific energies were calculated for the jet piercing drill to be 1.9 x 10^6 in.-lb/in.^{3} in granite.

5.2.2 Forced Flame Technique

The forced flame drill (Ref 7, pp 53-55) is very similar to the jet piercing drill except that nitric acid is used instead of oxygen. This method is still inefficient due to poor heat transfer and high flame speed. Specific energies were calculated to be slightly less than the jet piercing drill at 1.3 x 10^6 in.-lb/in.^{3}. Also, the high cost of nitric acid makes the forced flame technique prohibitively expensive.

5.2.3 Electric Disintegration Technique

An electric disintegration drill, shown in Figure 5.6, works by grounding high voltage (60 Hz) to the rock itself (Ref 7, pp 55-57). This technique is only good for rocks with high electrical conductivity or porous rock saturated with water.

Specific energy for the electric disintegration drill was calculated to be 4 x 10^5 in.-lb/in.^{3}.

5.2.4 Microwave Technique

A microwave rock drill is shown in Figure 5.7 (Ref 7, pp 65-68). It has been determined that, at frequencies of 1,000 to 3,000 Hz, rocks can be heated and fractured using microwaves. After 5 to 15 minutes of exposure, rocks form large cracks, causing 0.5-m^3 blocks to break off. It is estimated that the specific energy requirement for microwave devices in the field would be on the order of 4×10^5 in.-lb/$in.^3$. However, microwave devices do not work underwater since the water absorbs and reflects most of the energy. In addition, microwave devices typically have low power output, so that excavation rates [illegible] slow. Like the jet piercing technique, microwave devices can only excavate spallable rock.

5.3 FUSION AND VAPORIZATION OF ROCKS

The amount of heat necessary to fuse rocks must cause the rock to reach a temperature of 1,850° to 3,600°F.

5.3.1 Electric Heating Technique

Electrical heating of a tungsten resistance wire has been used to experimentally drill rock. Figure 5.8 (Ref 7, pp 65-68) shows the drill which heats up to 2,200° to 3,000°F to literally melt the rock. The drill requires 5 kW of power to operate. Boron nitride, which surrounds the tungsten wire, serves both as an electrical insulator and heat conductor. The molten rock is then extruded up a tube, where a stream of gas solidifies it into small glass-like particles (refer to Figure 5.8). Specific energy was calculated to be 3.28×10^6 in.-lb/$in.^3$ in basalt. Theoretically, only 1.3×10^6 in.-lb/$in.^3$ is required to fuse rock. Therefore, only 50% of the thermal energy is being transmitted to the rock. In addition, electric heating in an underwater environment would be impractical because of the high heat absorption of the surrounding water.

5.3.2 Electric Arc Technique

An electric arc drill (shown in Figure 5.9) drives a continuous arc (not sparks) at 10 to 1,000 volts to produce temperatures of 9,000° to 36,000°F (Ref 7, pp 77-81). This drill was tested underwater for fusing sandstone and was found to be 15% to 30% efficient. The tests indicated that the water absorbed much of the drilling energy. In addition, the electric arc technique has a high shock potential for divers.

5.3.3 Oxygen Lance

Battelle Center of Research at Geneva has developed an oxygen lance technique which involves the melting of rock by the oxidation of iron. The equipment consists of a hollow iron tube filled with a bundle of iron rods. Oxygen is passed down the tube and combustion initiated by an electrical spark at the lower end of the tube. The tube is then mechanically pushed into the rock at an advance rate of 1 fpm for a 1-inch-diameter hole. Approximately 300 liters of oxygen will oxidize 1 kg of iron to produce 2 kWh of energy. The flame from the reaction is about 6,500°F. Specific energy was calculated to be 9.29×10^4 in.-lb/in.^{3} for the oxygen lance.

5.3.4 Plasma Technique

Figure 5.10 shows an experimental plasma drill (Ref 7, pp 81-84). The plasma is produced by passing an electric current through a high velocity gas flowing between two electrodes. Ionized flame temperatures reach 3,600°F.

Tests showed that only 30% to 40% of the energy converted in the plasma drill is actually transferred to the rock. Specific energy for the plasma drill excavating granite was calculated to be 2.0×10^6 in.-lb/in.^{3}.

5.3.5 Electron Beam Technique

An electron beam rock drilling device is shown in Figure 5.11. Approximately 30 kV potential is required to accelerate electrons from the cathode to the anode. An electrostatic and electromechanical lens focuses these electrons in a beam against the rock (Ref 7, pp 84-86). The electron beam technique would pose a shock hazard for divers. Specific energies for electron beam devices are unknown.

5.3.6 Laser Technique

Experiments with laser power to cut rock show that the power output is too low and would require long exposures to heat the rock.

5.4 CHEMICAL METHODS

Chemicals have been used successfully for excavating sandstone, limestone, and granite (Ref 8). Figure 5.12 shows a chemical drill which uses fluorine to dissolve rock. The disadvantages of using chemicals for excavation are their high cost and the safety precautions necessary in handling large volumes. However, the products produced by chemical excavation are harmless. The chemical drill shown in Figure 5.12 is a one-shot device. After firing, the drill must be pulled out of the hole, recharged, and re-inserted. Specific energy requirements for this technique are not known.

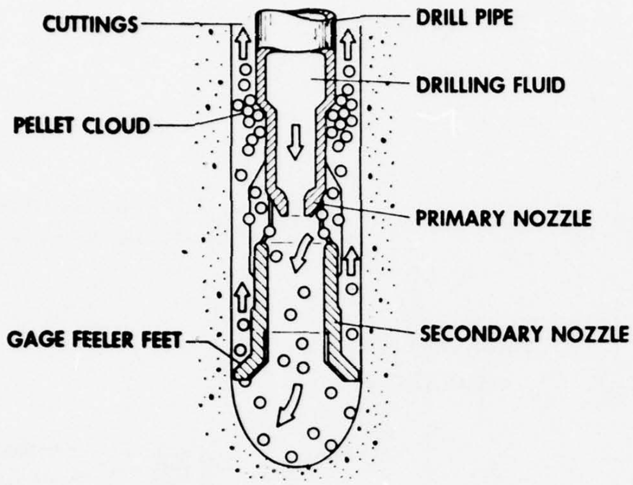

Figure 5.1. Pellet drill (Ref 29).

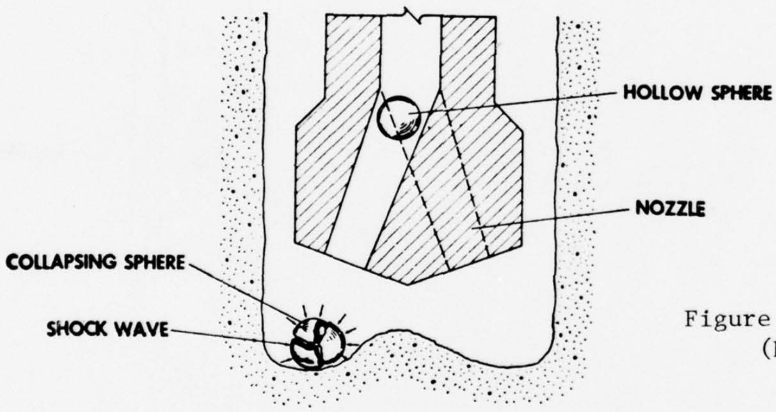

Figure 5.2. Implosion drill (Ref 7, pp 23-24).

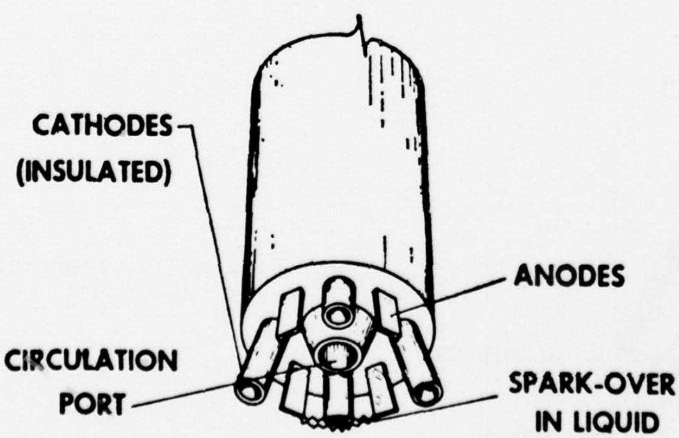

Figure 5.3. Spark drill (Ref 7, pp 24-29).

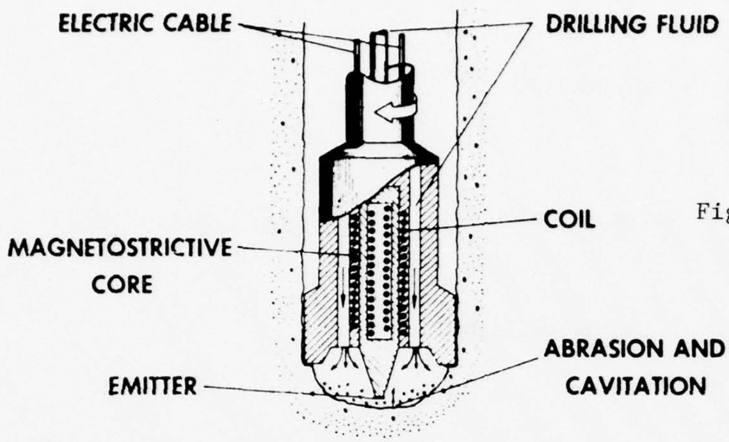

Figure 5.4. Ultrasonic drill (Ref 7, pp 44-49).

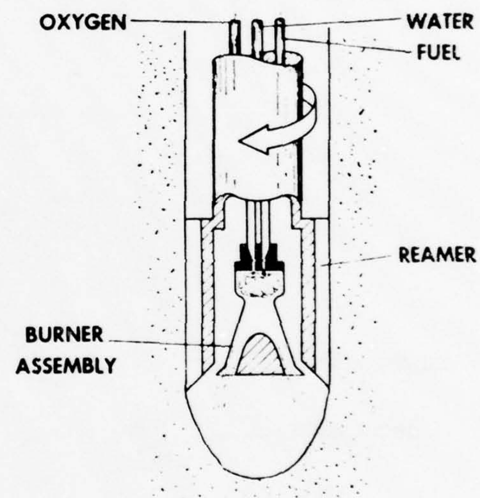

Figure 5.5. Jet piercing drill (Ref 7, pp 50-53).

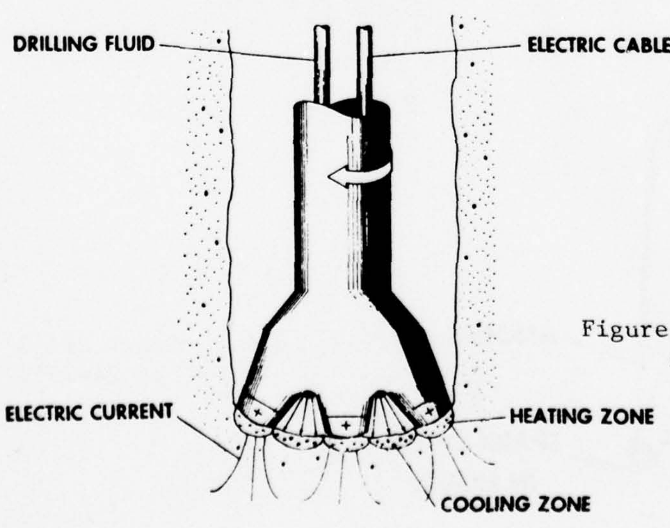

Figure 5.6. Electric disintegration drill (Ref 7, pp 55-57).

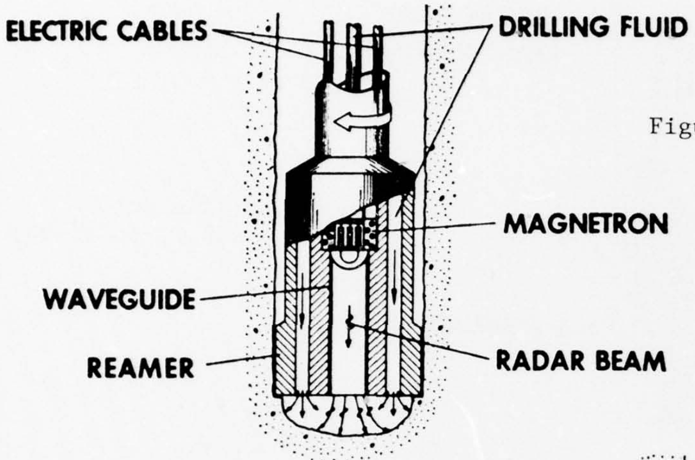

Figure 5.7. Microwave drill (Ref 7, pp 65-68).

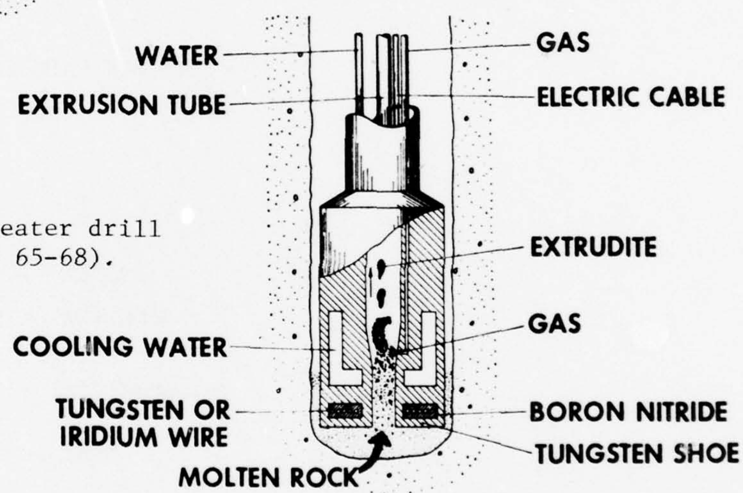

Figure 5.8. Electric heater drill (Ref 7, pp 65-68).

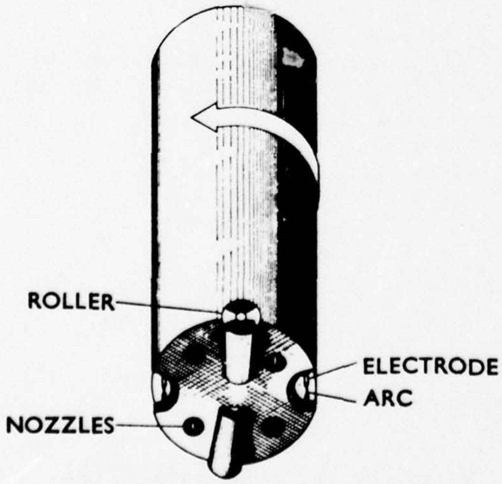

Figure 5.9. Electric arc drill (Ref 7, pp 77-81).

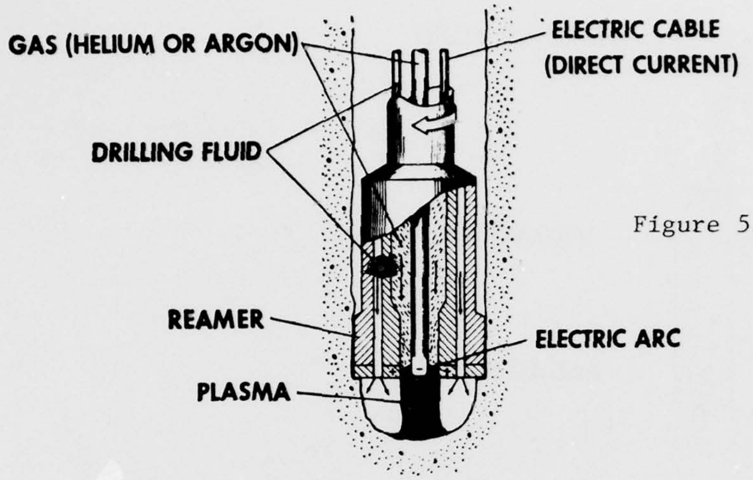

Figure 5.10. Plasma drill
(Ref 7, pp 81-84).

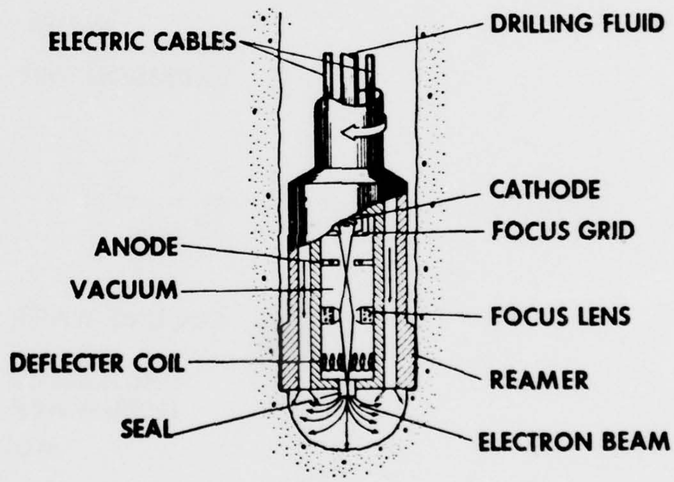

Figure 5.11. Electron beam drill
(Ref 7, pp 84-86).

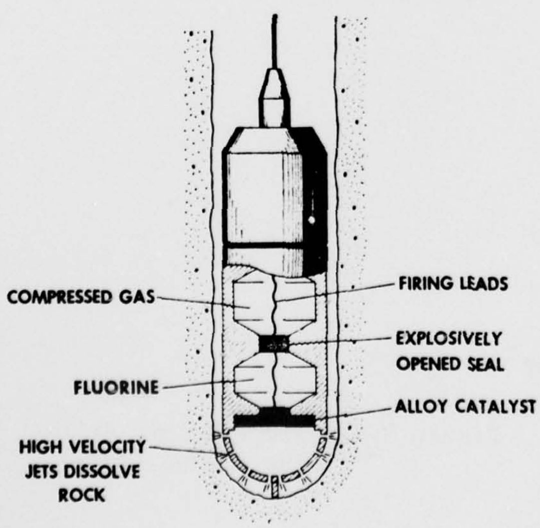

Figure 5.12. Chemical drill.

CHAPTER 6

EVALUATION AND PROBLEM IDENTIFICATION

The excavation equipment study of the previous chapters included all types of techniques applicable to nearshore trenching, ranging from common terrestrial machines to novel laboratory experiments. To eliminate all except those techniques promising improved performance to nearshore trenching, they were further evaluated with respect to the following categories:

(1) Effective power required to perform the job (efficiency)

(2) Ability to trench in a range of nearshore materials

(3) Adaptability to underwater use

(4) Development status

Each of these categories is discussed in this chapter and final overall ratings determined for the candidate method.

6.1 EFFECTIVE POWER RATING

All of the techniques discussed previously are listed in Table 5 in order of their power efficiencies. As discussed in Sections 1.4 and 1.5, the efficiency of a particular machine is inversely proportional to

its specific energy and performance index. Specific energy, the material in which the specific energy was calculated, and performance index are also shown. The performance index D was calculated from Equation 2,

$$D = \frac{E}{\delta} \qquad (2)$$

where E and δ were obtained from Table 5. To help evaluate the effective power requirements of these machines based on their specific energies, a theoretical horsepower requirement was calculated in column 5 for a baseline trench. The baseline trenching operation consisted of excavating a 10-inch-wide by 30-inch-deep trench at a forward traverse speed of 0.5 fpm in 17,500-psi sandstone. The theoretical horsepower required to dig this trench, using each of the techniques listed in Table 5, was calculated from their performance index and Equations 1 and 2. For a trenching machine with D = 1 (i.e., disc saw, ladder trencher, or cavitating waterjet) the specific energy was found for 17,500-psi sandstone to be:

$$D = \frac{E}{\delta} \qquad (2)$$

$$1 = \frac{E}{17{,}500 \text{ psi}}$$

$$E = 1.75 \times 10^4 \text{ in.-lb/in.}^3$$

Thus in the above example,

$$U = 0.5 \text{ fpm}$$
$$A = 2.08 \text{ ft}^2$$
$$E = 1.75 \times 10^4 \text{ in.-lb/in.}^3$$
$$\dot{V} = U(A) = 1{,}797 \text{ in.}^3\text{/min}$$

Knowing the specific energy, E, for a machine cutting in 17,500-psi rock, the theoretical power can then be calculated:

$$E = \frac{\dot{P}}{\dot{V}} \tag{1}$$

$$\dot{P} = E\,\dot{V}$$

$$\dot{P} = \left(1.75 \times 10^4 \ \frac{\text{in.-lb}}{\text{in.}^3}\right)\left(1{,}797\ \frac{\text{in.}^3}{\text{min}}\right)\left(\frac{1 \text{ ft}}{12 \text{ in.}}\right)\left(\frac{1 \text{ hp}}{33{,}000 \text{ ft-lb/min}}\right)$$

$$\dot{P} = 79 \text{ hp}$$

Therefore, the disc saw, ladder trencher, and cavitating waterjet all theoretically require 79 hp to excavate the baseline trench.

Figure 6.1 is a nomograph showing the functional relationship between trench cross-sectional area, traverse speed, specific energy, and theoretical horsepower. Using the baseline trench given in the above example, the theoretical power required for each trenching mechanism can be found from the nomograph as follows:

(1) On Figure 6.1, start at U = 0.5 fpm and move horizontally to the right at the intersection of the trench cross section, $A = 2.08 \text{ ft}^2$.

(2) Drop straight down to $E = 1.75 \times 10^4$ and move back horizontally to the left and read the horsepower.

For the examples shown above, 79 hp is the theoretical power required by the trenching mechanism.

For a trenching machine with D = 3.5 (i.e., jackhammer or impactor),

$$D = \frac{E}{\delta}$$

$$3.5 = \frac{E}{17{,}500 \text{ psi}}$$

$$E = 6.1 \times 10^4 \text{ in.-lb/in.}^3$$

From Figure 6.1, the required power for a trencher using a jackhammer impact mechanism would be 280 hp to cut the same baseline trench. Thus, the impactor technique requires almost four times the power required by the ladder trencher or cavitation waterjet.

For evaluation purposes, the horsepower required to cut the baseline trench by each of the trenching techniques is given in column 5 of Table 5. The trenching techniques were then rated good, fair, or poor, based on the power required to excavate the trench. These ratings are listed in column 6 of Table 5. Trenching techniques requiring less than 100 hp are considered good, efficient machines. Those between 100 and 1,000 hp are considered fair (tolerable in the field in special cases). Those machines requiring over 1,000 hp are considered poor candidates and are eliminated from further consideration: machines rated good are considered primary trenching candidates; machines rated fair are considered candidates for augmenting primary trenching machines.

In the above example, the cavitating waterjet is rated as efficient as the ladder-type trencher or disc saw. However, it should be noted that the cavitating waterjet's specific energy is based on small-scale laboratory experiments only, while specific energies for disc saws and ladder trencher were calculated from full-scale operating trenchers. All excavation techniques from Table 5 rated good or fair (based on their power efficiency) are considered possible trenching candidates for further evaluation. The disc saw, rotary drag bit trencher, and ladder trencher have very similar excavating mechanisms. Therefore, these three techniques are grouped into one category called drag bit trencher.

6.2 MATERIAL PERFORMANCE RATING

It is important to know that the cutting power efficiency of a machine does not take into account any physical limitations of the machine. One physical limitation is the type of material the machine is capable of excavating. Table 6 lists the remaining candidate trenchers (obtained from Table 5) along with the range of material each machine is capable of excavating. From Table 6, both the cavitating waterjet and percussive jackhammer can cut a wide range of materials. Therefore, their material performance ratings are considered good. The drag bit

trencher and spark discharge mechanisms can cut medium soft to hard rock material only and are rated fair. The bucket trencher and waterjet plow* can cut only a narrow range of materials and are rated poor.

6.3 ADAPTABILITY TO UNDERWATER USE

Table 7 shows the six candidate trencher mechanisms and their ratings. The power efficiency ratings were obtained from Table 5, and the material performance ratings were taken from Table 6.

The candidate trenchers were then rated for adaptability for use in the underwater environment. Since the cavitating waterjet, waterjet plow, and spark discharge techniques have no moving parts at the seawater/trench interface, they are rated good for underwater adaptability. Experience gained from the PMTC trencher (Chapter 4) showed that trenching underwater using a modified mechanical trencher (disc saw or ladder trencher) is feasible but limited by the amount of preventive maintenance required. Any impact or abrasive-inducing machine requiring mechanical moving parts in seawater would always be subject to high maintenance costs and mechanical breakdowns. For this reason, the drag bit trenchers, bucket trencher, and percussive impactor are all rated fair for underwater adaptability.

6.4 DEVELOPMENTAL STATUS

Ratings for the developmental status of each of the candidate trenchers are also shown in Table 7. The cavitating waterjet is still in the developmental stage, but recent advances have been made in cavitating waterjet technology. Specific energies and performance are improving to the point where development of the waterjet for nearshore

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*The bucket trencher is designed primarily for excavating soils. The waterjet plow was designed for cutting coal.

trenching looks promising. The drag bit trencher and bucket trencher are proven successful terrestrial trenchers. Experience with the PMTC trencher has shown that modification of these mechanical trenchers for nearshore use is feasible. However, adaption of a terrestrial machine to the nearshore environment requires an extensive modification program. The percussive impactor has never been incorporated into a large trenching machine. All experiences with this type of mechanism have been with hand-held jackhammers; its development status for nearshore trenching is poor. The spark discharge technique is still considered novel, and its development as a trencher is still in the future. Therefore, the spark discharge and impactor are not considered at a suitable developmental stage for nearshore trenching. Of the remaining trencher candidates, the cavitating waterjet and drag bit trencher are recommended as primary candidates for nearshore use, primarily based on their good power efficiency and material performance. The percussive impactor and spark discharge techniques are listed as possible methods for augmenting one of the primary candidates. The bucket trencher and waterjet plow are not recommended for nearshore use. Since the disc saw and ladder trencher are basically the same, their ratings were identical. From the discussion in Section 2.3, the ladder trencher is more versatile than the disc saw for varying trench sizes. Of the two mechanical techniques, the ladder trencher is recommended over the disc saw. Therefore, the remaining two techniques recommended for evaluation as the primary mode for nearshore trenching are the ladder trencher and cavitating waterjet.

6.5 COMPARISON OF THE CAVITATING WATERJET WITH THE LADDER TRENCHER

The cavitating waterjet and ladder drag bit trencher are the two remaining candidate techniques that can significantly improve nearshore trenching. Laboratory experiments indicate that the cavitating waterjet has a good power efficiency and is well-adapted to the submerged underwater environment; however, it is the least developed of the two techniques.

The ladder trencher requires the least amount of development prior to full-scale nearshore trenching. Estimates indicate, however, that a trencher of this kind, with mechanical moving parts at the seawater/ trench interface and expendable cutter bits, will require 3 hours of maintenance "down-time" for every 5 hours of trenching (Ref 15). A comparison of performance features of the cavitating waterjet and the ladder trencher is listed in Table 8.

6.6 PROBLEM AREA IDENTIFICATION

The intent of this report is to evaluate the technology base for the design of the nearshore trenching mechanism. It is not the intent here to cover the design of other systems, such as carrier vehicle, power systems, and vehicle control. It should be mentioned that the design of the trenching mechanism directly affects the design of all support equipment. Regardless of the type of cutting mechanism used - mechanical or waterjet - support requirements must be considered in the design of a nearshore trencher. A review of support considerations and their related problems is given in Appendix A.

Specific problem areas with each of the trenching mechanisms (waterjet and mechanical) are discussed below.

6.6.1 Cavitating Waterjet

Up to now, only small-scale laboratory experiments have been performed on actual rock excavation using the cavitating waterjet. One problem when estimating power requirements for full-scale trenchers is scaling up these values based on specific energies taken in the laboratory. There is definitely a need for larger-scale data to accurately predict waterjet trenching requirements. Other problem areas include:

(1) Developing a means of maintaining the waterjet nozzles at a proper standoff distance within the trench

(2) Developing a means of efficiently operating the cavitating jet above water level or on the beach

6.6.2 Ladder Trencher

Before this type of trencher can be properly adapted for use in the nearshore environment, a number of problem areas must be identified and resolved:

(1) All existing terrestrial trenchers are designed to operate on presurveyed, cleared roadways.

One major problem when cutting into the ocean bottom with a bottom crawling/ladder-type trencher is keeping the cutter bar properly inserted in the trench while negotiating seafloor obstacles. The inability to do this results in damage to the cutter bits, cutter bar, and chain. The three following trencher functions must be controlled when trenching over irregular bottom conditions:

a. Trench depth

b. Cutter bar cutting angle

c. Cutter bar tilt due to vehicle roll

To control these functions, an articulated cutter assembly is necessary. Appendix B describes several design concepts for a ladder trencher-articulated cutter assembly.

(2) No data are available on how long carbide-tipped cutter bits will last in the sandy environment. Terrestrial trenches made from drag bit trenchers in sandy slate and sandstone proved uneconomical to commercial contractors. The abrasive characteristics of this material caused excessive wear on the carbide bits and chain.

(3) Seawater will act as a coolant on the cutter bits and help increase their performance when submerged; however, no test data exist to determine if the performance increase is significant.

Table 5. Summary of Excavation Techniques

Technique	Specific Energy (psi)	Rock Type[a]	D	Horsepower for Trench[b]	Efficiency Rating
Cavitation jet	2.0×10^{3}	granite	1	79	good
Disc saw	3.5×10^{3}	medium strength	1	79	good
Ladder trencher	3.8×10^{3}	medium strength	1	79	good
Rotary drag bit	5.3×10^{3}	soft strength	1	79	good
Bucket trencher	10.5×10^{3}	soil	–	–	good
Waterjet plow	3.2×10^{3}	coal	1.1	85	good
Percussive jackhammer	1.0×10^{5}	granite	3.5	280	fair
Spark discharge	6.1×10^{4}	weak sandstone	12	950	fair
Oxygen lance	1.0×10^{5}	concrete	–	–	poor
Electric disintegration	4.0×10^{5}	high conductive	37	3,000	poor
Forced flame	1.3×10^{6}	granite	44	3,500	poor
Microwave	4.0×10^{5}	medium strength	55	4,400	poor
Jet piercing	1.9×10^{6}	granite	63	5,000	poor
Plasma	2.0×10^{6}	granite	69	5,500	poor
Pellet drill	1.1×10^{6}	limestone	162	12,800	poor
Pulsed jet	7.2×10^{5}	–	–	–	poor
Continuous jets	5.7×10^{6}	granite	190	15,000	poor
Electron beam	3.2×10^{6}	medium strength	298	24,000	poor
Laser	3.2×10^{6}	medium strength	298	24,000	poor
Ultrasonic	1.5×10^{7}	–	500	40,000	poor
Electric heater	3.3×10^{6}	basalt	596	47,500	poor
Electric arc	2.7×10^{7}	sandstone	3,680	300,000	poor

[a]Rock type from which the specific energy was calculated.

[b]10 in. x 30 in. trench/0.5 fpm in 17,500-psi sandstone.

Table 6. Excavated Material Performance

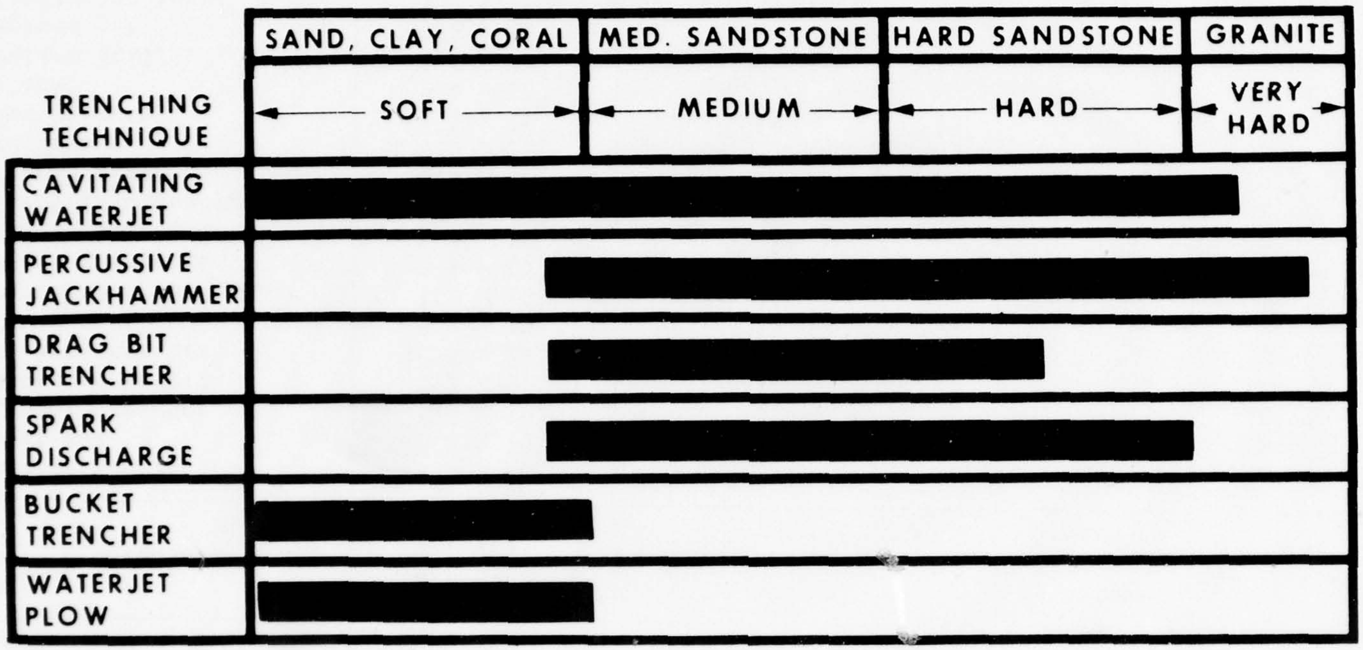

Table 7. Trencher Ratings

Candidate Trencher Mechanisms	Power Efficiency Rating	Material Performance Rating	Adaptability to Underwater Rating	Development Status	Recommended Usage
Cavitating waterjet	good	good	good	laboratory data promising	primary
Drag bit trenchers	good	fair	fair	terrestrial trenching	primary
Bucket trencher	good	poor	fair	terrestrial	not recommended
Waterjet plow	good	poor	good	experimental	not recommended
Percussive impactor	fair	good	fair	no trenching development	augmentation
Spark discharge	fair	fair	good	novel technique	augmentation

Table 8. Performance Features

Cavitating Waterjet	Drag Bit Trencher
1. Still under development, lab tests show promising results	1. Field well-developed; experience gained with full-scale machines
2. No power density limtation	2. Cutters limited to 40 hp/sq ft of trench contact area
3. Operates more efficiently when submerged	3. Operates above water or submerged at the same efficiency
4. Efficiency increases with depth	4. Not depth sensitive
5. No nozzle wear	5. Heavy wear on carbide bits; subject to breakage
6. No cutter replacement maintenance	6. Periodic diver maintenance and cutter replacement
7. Cutter not affected by material abrasion	7. Abrasive material causes high cutter wear rates
8. Zero moving parts in the trench	8. Has chain drives, bearings, sprockets
9. Active system necessary to maintain proper standoff	9. No standoff
10. Very noisy underwater	10. Moderately noisy underwater
11. Leakage of working fluid (seawater) causes no environmental damage	11. Hydraulic fluid leaks damaging to the environment

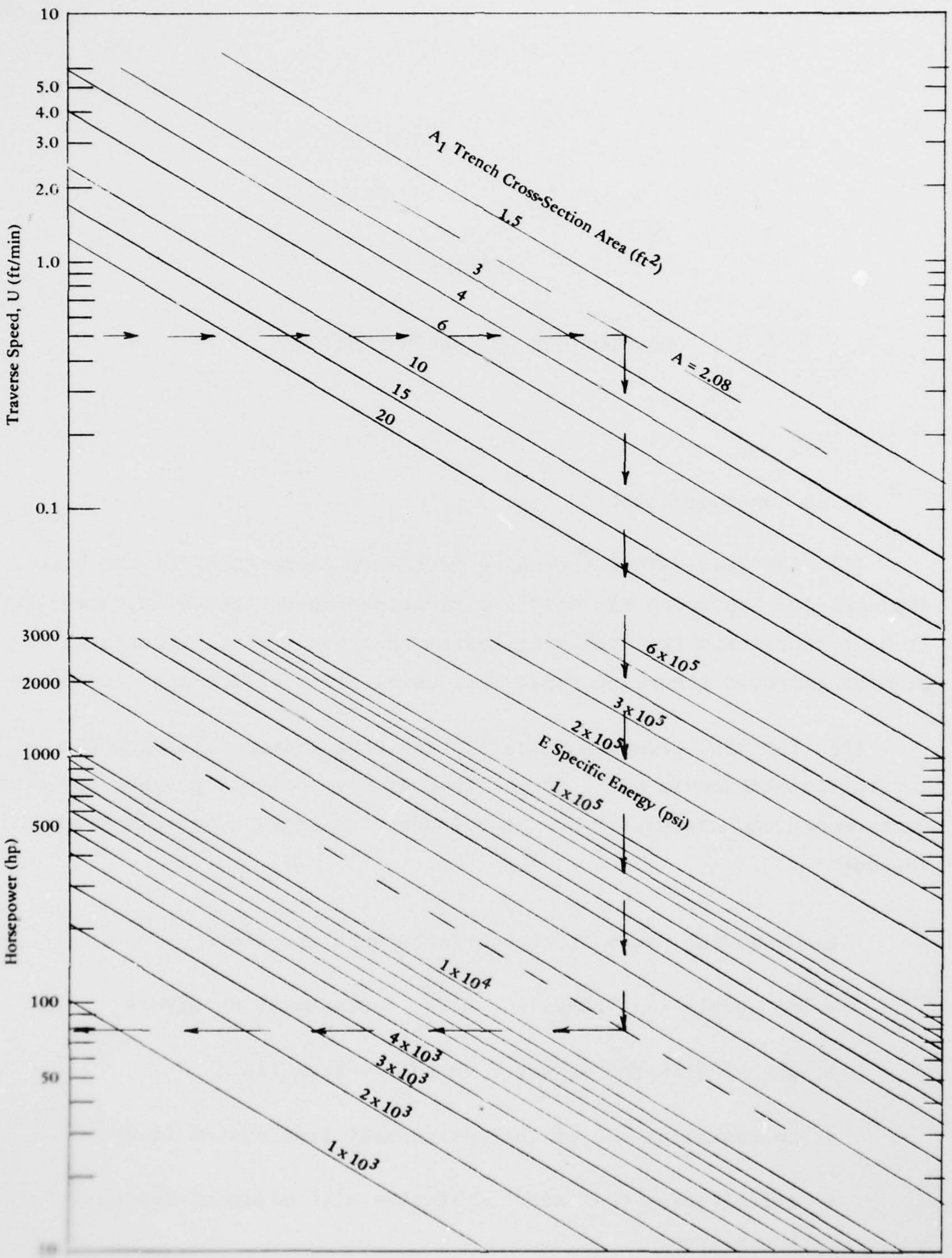

Figure 6.1. Nomograph of various functional relationships.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that:

(1) The ladder-type trenching mechanism seems to offer the best approach for improving the Navy's current nearshore trenching capability. It best represents the trenching system that can (with limitations) provide improved trenching capability using state-of-the-art technology.

(2) The high-pressure waterjet trenching system utilizing the cavitation phenomenon will, at the cost of development, provide improved performance and capability over the ladder trencher. These improvements include:

- no moving parts at the cutter/trench interface
- no nozzle wear, thus no cutter replacement by divers
- use of filtered seawater as the working fluid
- no contamination of the environment from system leaks
- efficiencies that are competitive with state-of-the-art techniques

- relatively simple and compact support equipment
- use of off-the-shelf medium pressure with readily available reliable hardware

The cavitating waterjet and ladder-type trenchers each have specific individual problems when used for nearshore trenching. The cavitating waterjet is expected to provide the most significant performance improvements of the two systems. However, nearshore development on ladder-type trenchers is closer to state-of-the-art. Before a logical choice can be made between the two systems, it is recommended that further research and development be conducted for both approaches as described below.

(1) Determine the specific energy and trenching capability of cavitating waterjets on larger-scale trenches.

(2) Determine the ability and practicality of an articulated mechanical cutter assembly to properly maintain trench depth, cutting angle, and cutter tilt.

(3) Determine the effective wear rates of carbide cutter bits operating in abrasive sand.

(4) Determine the level of improved performance of the drag bit due to the cooling effect of seawater.

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Appendix A

SUPPORT REQUIREMENTS

Regardless of the type of cutting mechanism used, the following support requirements must be considered in the design of a nearshore trencher:

(1) Type of carrier vehicle and means of propulsion

(2) Power system requirements

(3) Control and guidance of the vehicle

(4) Excavated material removal system

(5) Trencher deployment requirements

A.1 CARRIER VEHICLE

For the nearshore trencher, candidate carrier vehicles include sleds, tracked vehicles, wheeled vehicles, or surface vessels. A towed sled would be similar to a deep-sea plow; a tracked vehicle would be similar to a caterpillar tractor; a wheeled vehicle would be similar to a swamp buggy; and a surface vessel would be similar to a dredge. The sled would be towed either from the surface or bottom. The other three vehicles would be self-propelled.

Based on the trencher state-of-the-art assessment in Reference 13, it was determined that a track vehicle was the most feasible approach for the nearshore trencher. The design of the track system and support chassis is constrained by two requirements:

(1) The track system must be capable of supporting the entire weight of the machine in the surfzone where mechanical vibration and surf action liquify and erode the supporting sand. This causes excessive sinkage and track slippage as experienced with the PMTC trencher (discussed in Chapter 4). This requirement dictates a very wide track with a large contact surface area to minimize ground bearing force.

(2) The track system must also operate in irregular terrain. Often the vehicle will experience sandy and rocky terrain at the same site. This environment dictates a very rugged, heavy track. Each shoe of the track must have sufficient strength to support the entire weight of the vehicle. Therefore, the track system must have a wide contact area on the sand and be extremely rugged for rough terrain.

The size and weight of the track units will depend largely on the payload they support (i.e., trenching mechanism, power units, cable reels). During the nearshore trenching state-of-the-art study (Ref 13), various trencher/track unit concepts were evaluated. Figure A.1 shows the interrelationship of a ladder trenching mechanism and power cable reel with a two-track, three-track, and four-track system. Figure A.2 shows similar track systems supporting a disc saw trenching mechanism. An excellent analysis of track unit concepts are presented in Reference 13.

A.2 POWER SYSTEMS REQUIREMENT

A.2.1 Mechanical Trencher Power Units

There are two alternatives for generation and transmission of power to a mechanical trencher that are state-of-the-art. A block diagram of each is shown in Figure A.3. A brief description of each power system concept is presented below.

(1) Electric. A diesel engine driving an electric generator on shore is the source of the electrical power. The power is delivered to the trencher through an electromechanical cable. The data and control circuits are also housed in the electromechanical cable. Each end of the cable is terminated in a wet mateable connector. A cable reel located on the trencher provides storage for the tether. During trenching operations the tether is deployed from the cable reel as the trencher leaves the shore and is retrieved on the return trip. Power for all of the vehicle's subsystems is derived from the output shaft of the main electric motor.

(2) Hydraulic. The primary hydraulic pump is driven by a diesel engine located on a support platform. A tether consisting of the supply hose, return hose, and the electrical data/control cable connects the hydraulic power source to the trencher. Hydraulic quick disconnects and wet mateable electrical connections will be installed at each end of the tether. Hose reels can be located on the support platform, trencher, or both, depending on operational requirements. The hydraulic power delivered to the trencher drives the main hydraulic motor from which all vehicle subsystems are powered.

A.2.2 Water Power Units

The power unit size and weight are determined by the trenching power requirement. Figures A.4 through A.6 show commercially available waterjet power units. Figure A.4 is a 130-hp, tandem trailer-mounted, diesel-powered unit capable of 10,000-psi pressure. Total unit weight is 7,700 pounds. Figure A.5 is a 700-hp mobile intensifier. This unit is also diesel powered, capable of 20,000-psi pressure. Figure A.6 is a trailer-mounted, 1,000-hp power unit capable of delivering 20,000 psi. This unit is powered by a gas turbine engine. A typical block diagram for the 700-hp diesel intensifier is shown in Figure A.7.

A.3 CONTROL AND GUIDANCE

There are basically three types of controls to consider for near-shore trenching: automatic, remote, and local control. Totally automatic controls are expensive and complicated. Remote control requires sensors and visual monitoring equipment. Local control requires divers at all times in and around the operating trencher. From a diver safety standpoint, local control would not be acceptable, especially if the trencher was electrically powered. Remote control appears to be most feasible.

For a mechanical ladder trencher, sensors would be required to monitor:

(1) Steering

(2) Cutter depth

(3) Feed rate (advance speed)

(4) Cutter bar angle

(5) Cutter side load

For a waterjet trencher, a standoff sensor would be required in addition to those listed above.

A.4 MATERIAL REMOVAL

Material removal refers to the transport of the cuttings out of the trencher and away from the work area. Terrestrial trenchers use various types of conveyor belts or chain buckets to convey the material out of the trench. However, experience has shown that conveyor belts do not work underwater (refer to Section 4.2). In the case of a ladder trencher, the cutter mechanism could incorporate buckets in addition to

its cutter bits. Fluid transport of cuttings may be another solution. A slurry with water or air as the carrier fluid may be pumped, jetted, or sucked out of the trench. This method would probably be used in conjunction with high-pressure waterjet trenchers.

If a cable is being buried simultaneously with the trenching operation, it may not be necessary to transport the cuttings out of the trench. Instead, a cable chute, shown in Figure A.8, can be used to keep the trench open only long enough for the cable to be inserted. In Figure A.8, the cable chute is dragged immediately behind the cutter disc. The cable is constantly fed down through the chute and into the trench. As the chute passes by, it closes the trench, leaving the cable buried.

A.5 TRENCHER DEPLOYMENT

A typical operating scenario involves deployment of the trencher and its support modules to the beach site by truck. At the beach site the equipment will be assembled and prepared for operation. The control and power modules on the beach will be connected to the trencher by a power/control umbilical tether. The umbilical will have a minimum length of 2,500 feet, thus allowing almost 1/2 mile of trench to be dug without requiring ship support. As the trench is dug seaward from the beach, the umbilical is deployed from a reel located on, or towed behind, the trencher. If a longer trench is required, a surface support platform moored approximately 5,000 feet from shore on to which the power and control modules could be transferred would enable almost 1-1/2 miles of trench to be dug. Deployment and operational control of the trencher from a surface platform will be a project option (dependent, however, on feasibility of the support platform to be safely moored and positioned throughout the trenching operation period).

All normal operations of the trencher shall be remote-controlled from the beach site. All digging operations will be along routes which are presurveyed and cleared (to within the operating limits). Opera-

tions may include simultaneous digging and laying functions (i.e., the cable/pipe will have already been laid along the track, and the trencher will underrun the cable/pipe as it trenches). Divers will be used during trenching operations to assist (using local override features) in the initial setup, to monitor the trench cutting along the route, and to verify the success of simultaneous cable/pipe laying operations.

The trencher and its support equipment must be modularized to the extent that breakdown for truck or air transport is possible. However, when the equipment arrives on site, it must be capable of commencing trenching operations within 12 hours setup time. Equipment required to support the setup/breakdown operation must be limited to that transportable by truck to the beach site and as available from the Naval Construction Forces Standard Table of Allowance.*

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*CESCO computer printout UCT Table of Allowance, Part I TA-04, TA-05. (Updated regularly)

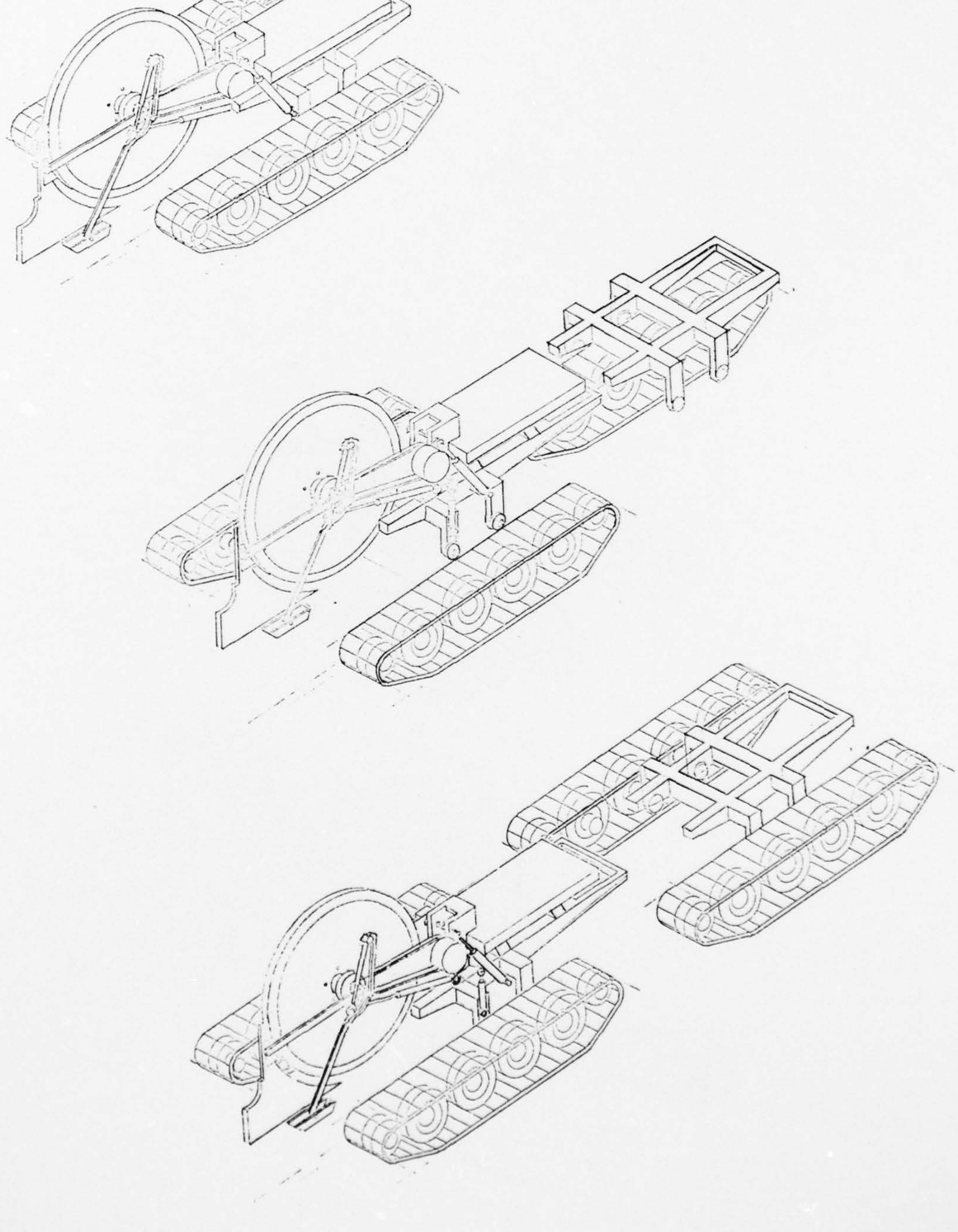

Figure A.2. Disc trencher configurations.

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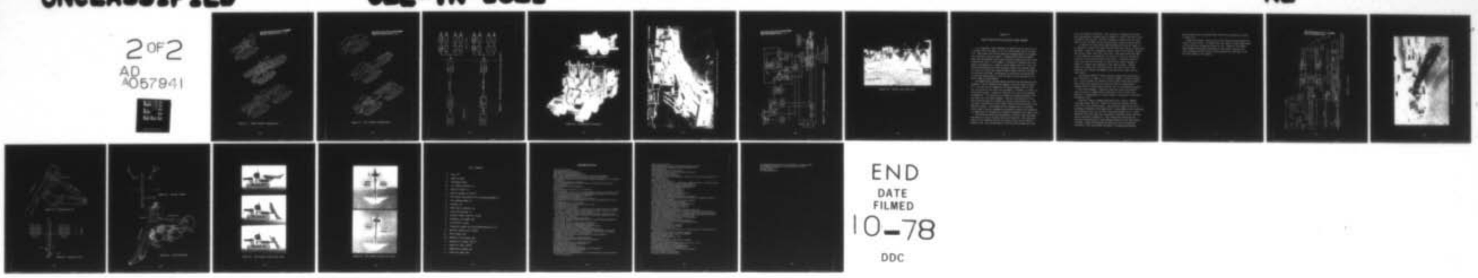

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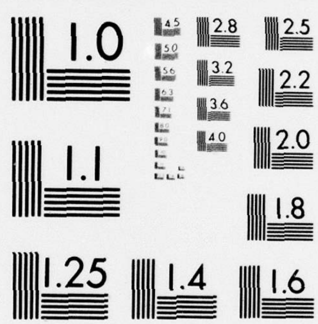

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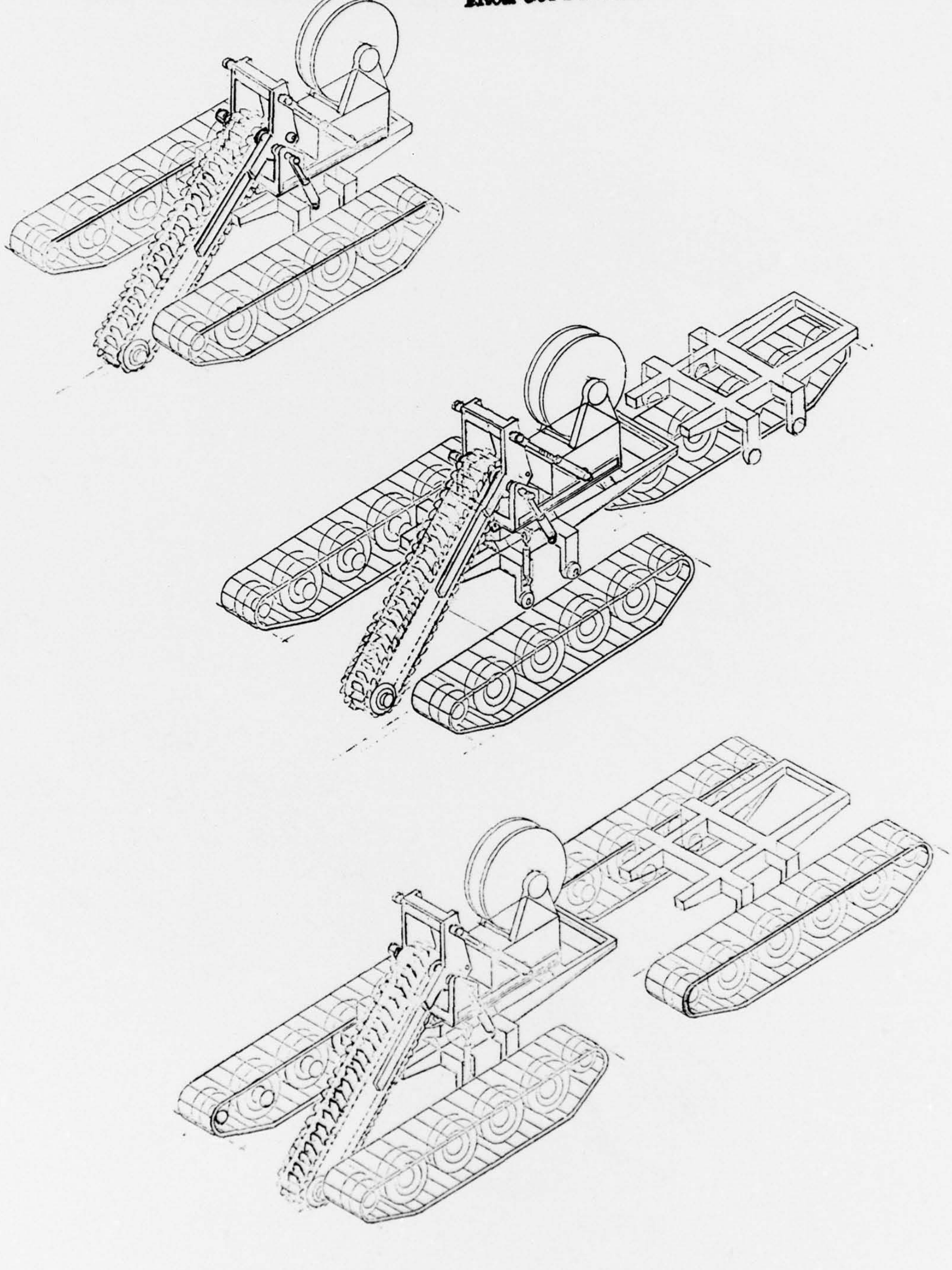

Figure A.1. Ladder trencher configurations.

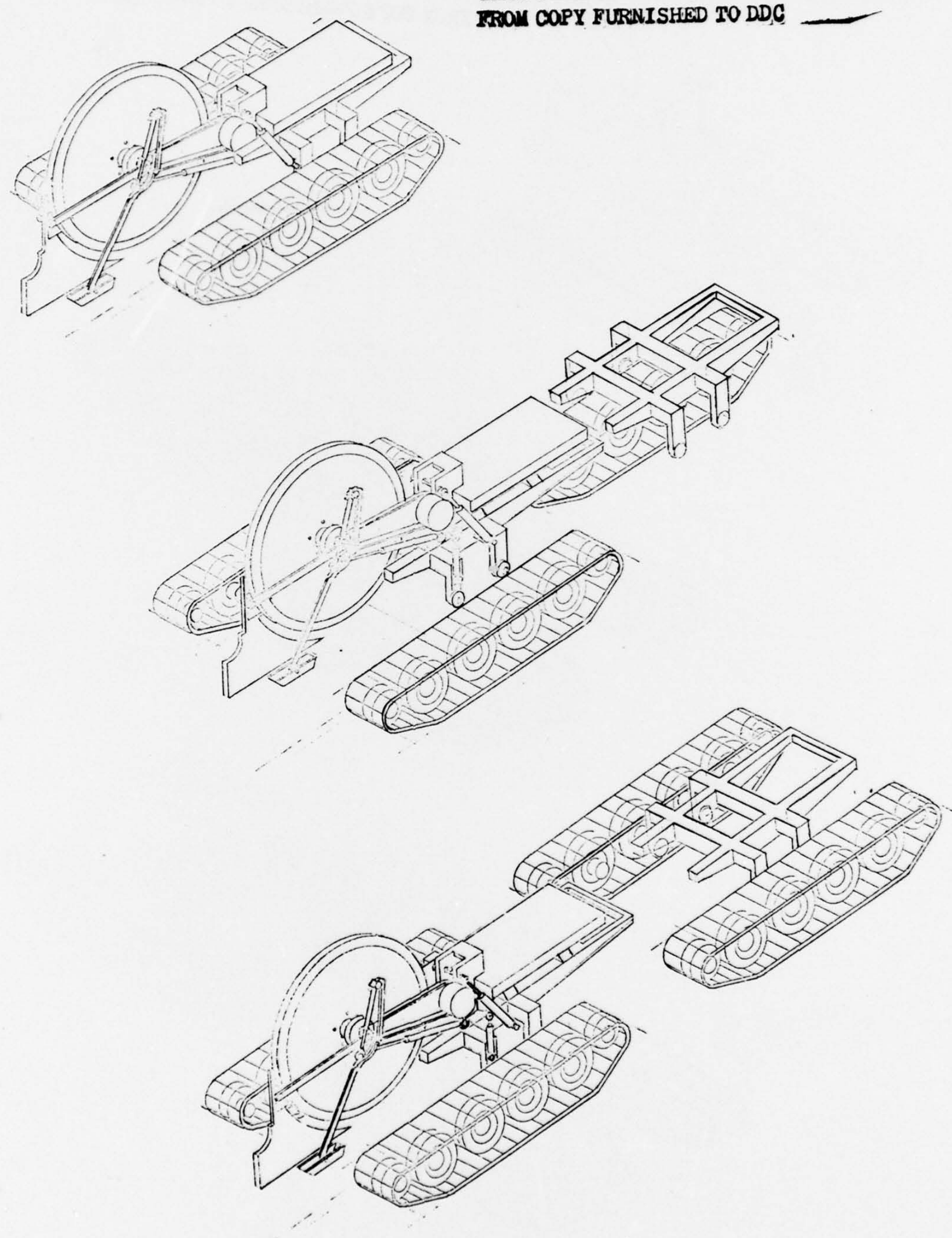

Figure A.2. Disc trencher configurations.

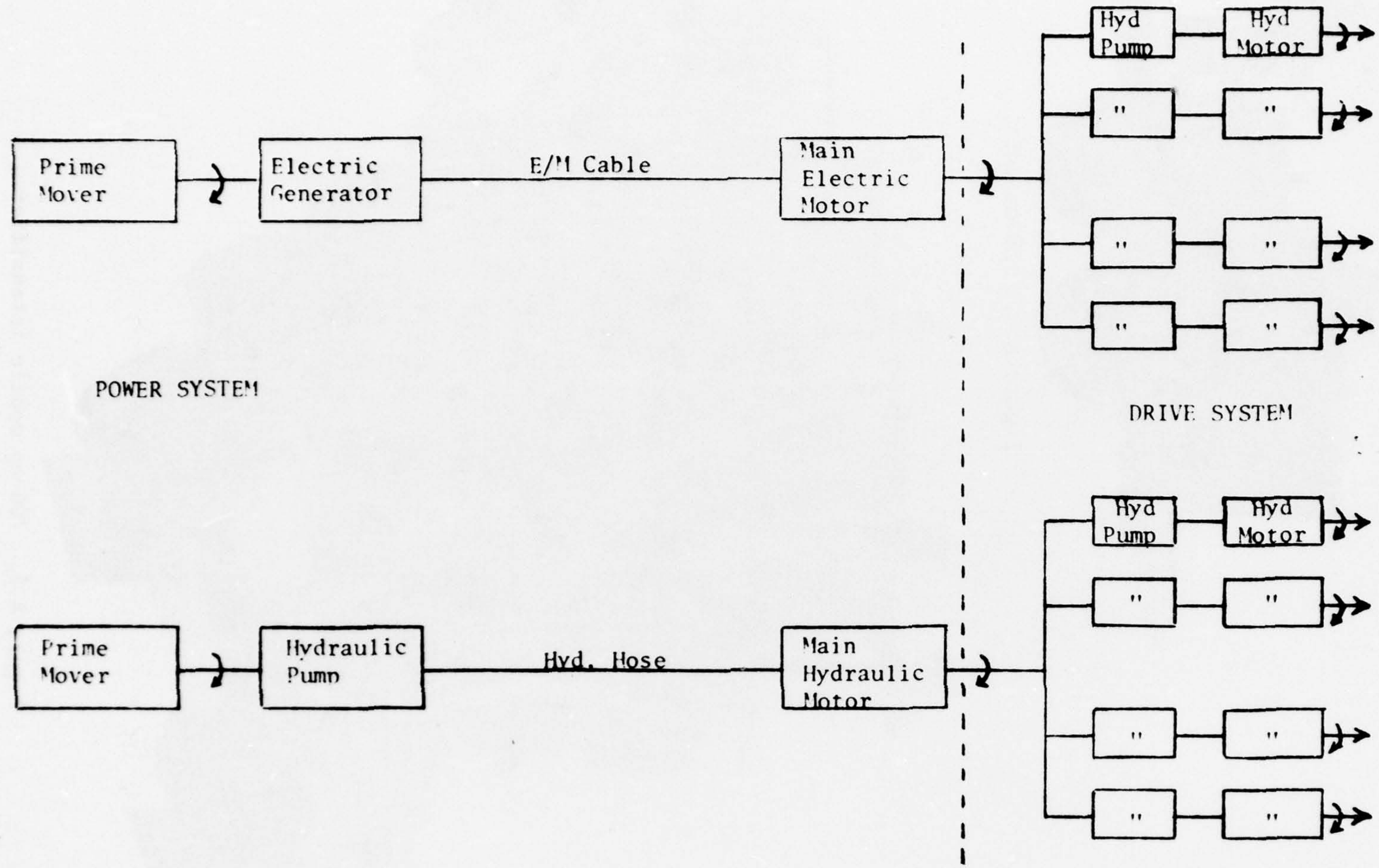

Figure A.3. Block diagram of power and drive system components.

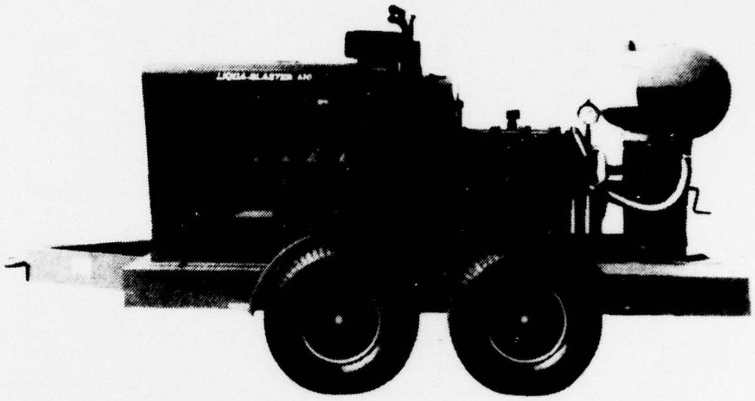

Figure A.4. 130-hp unit.

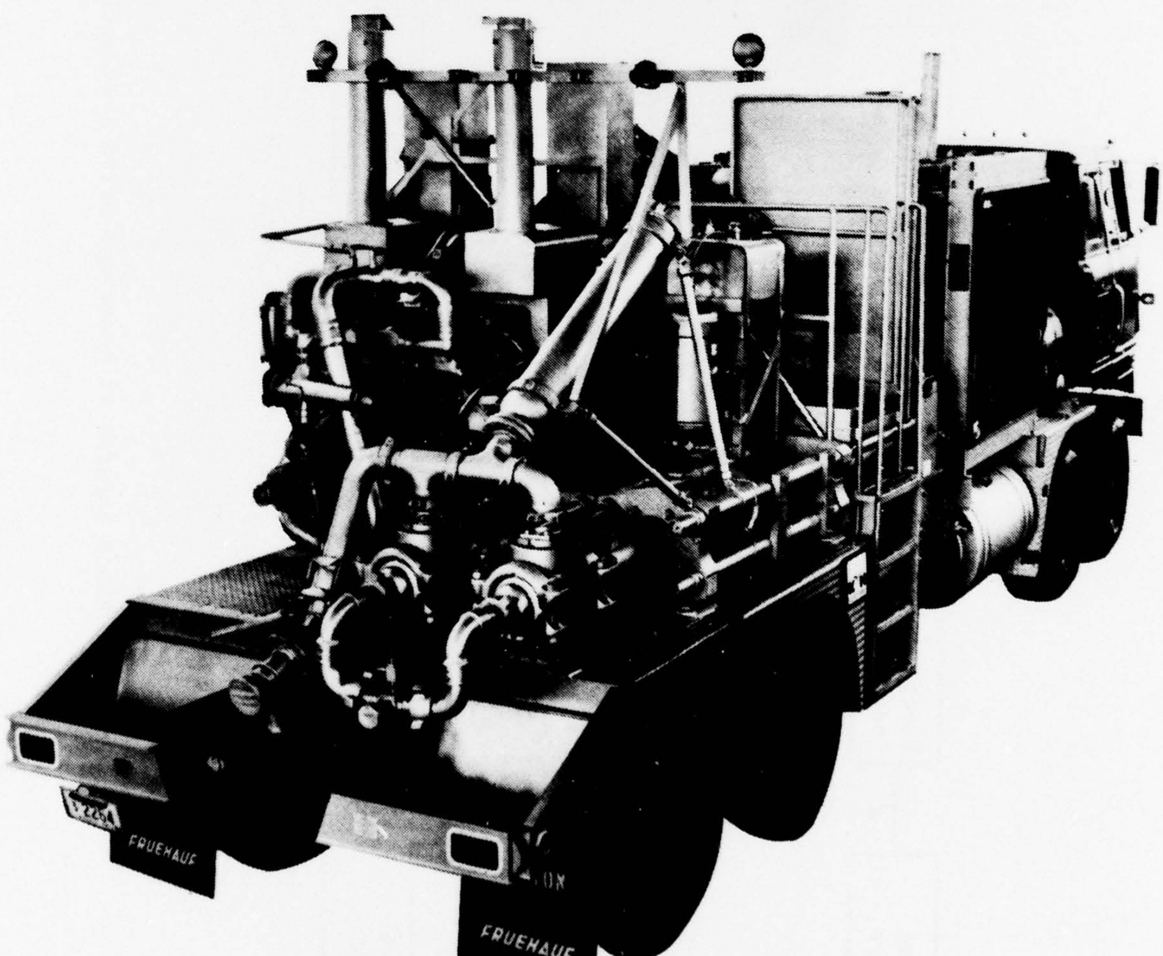

Figure A.5. 700-hp mobile intensifier.

Figure A.6. 1,000-hp, gas-turbine powered mobile intensifier.

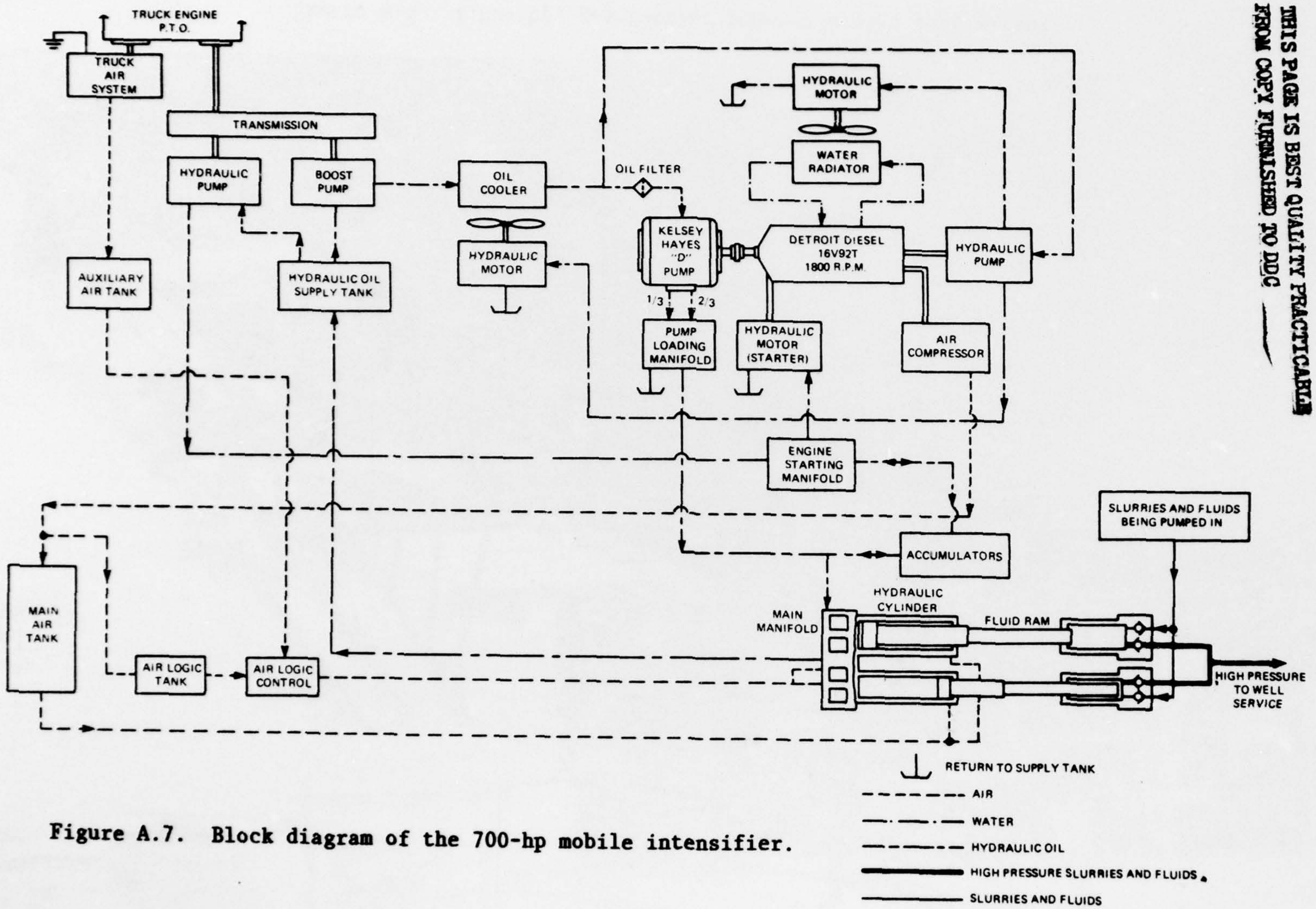

Figure A.7. Block diagram of the 700-hp mobile intensifier.

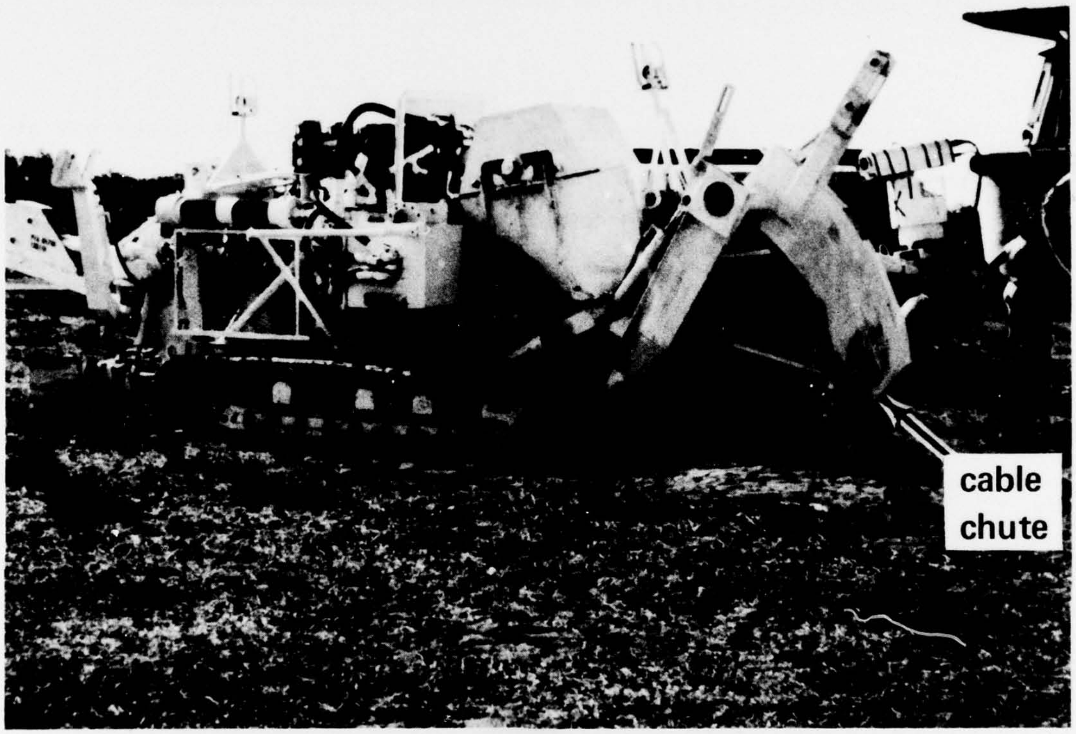

Figure A.8. Trencher with cable chute.

Appendix B

DESIGN CONCEPTS FOR AN ARTICULATED LADDER TRENCHER

It is important, when trenching, to operate with the cutter bar at a constant cutter bar angle, ϕ, for all trench depths (refer to Figure 1.1). Both cutter tool relief angles and chipping depths are designed for a specified cutter bar angle. Trenching with cutter bar angles other than the designed value causes excessive tangential forces on the carbide cutter bits. As an example, to maintain a constant cutter bar angle of 60 degrees for a range of trench depths from 3 to 7 feet, the articulated boom must be raised through an angle of 30 degrees, while the cutter bar itself must swing through an angle from 60 to 90 degrees in relation to the boom. By swinging the cutter bar and raising the cutter boom simultaneously, cutter bar angle is held constant for the entire range of trench depths.

One commercially available machine which has an articulated cutter assembly is the Joy Manufacturing Company's Coal Saw, shown in Figure B.1. The coal saw is designed for cutting horizontal slots in coal, but, by rotation of the cutter bar 90 degrees, it becomes, in effect, an articulated trencher. Figure B.2 shows the coal saw in the trenching configuration. The cutter boom is capable of raising 30 degrees, and the cutter bar can swing 90 degrees. The Joy Coal Saw has, in fact, been tested and used as a trencher on several occasions (Ref 15). The Joy report concluded that their ladder trencher definitely requires flat ground to operate. Even though the Joy trencher has an articulated cutter boom, it was not equipped with automatic controls and, therefore, was impossible for the operator to manually compensate over rough terrain.

An alternative method for maintaining a constant cutter bar angle with depth is to use a sliding cutter bar, Figure B.3. The cutter bar angle is first adjusted and set with respect to the cutter boom by a hydraulic ram. The cutting depth is then varied by sliding the cutter

bar up or down the slide guide. This concept for changing trench depth while maintaining a constant angle is simpler to control than the articulated boom of the coal saw. With the sliding bar concept, once the cutter angle is set, the depth can be controlled with a single sliding actuator.

In addition to controlling trenching depth and cutter bar angle, it is important to control the cutter bar tilt while the vehicle is negotiating obstacles. Figure B.4 represents a head-on view of the trencher, showing the vehicle tracks, cutter bar, and trench. The figure shows that when a 2-foot obstacle is encountered, one track will raise up, causing the cutter bar to jam into the side of the trench. To properly align the cutter bar back into the trench, it must be both rotated through an angle of 11 degrees and translated to the right 8 inches. Without proper tilt control, the rolling action of the vehicle would cause excessive side loading, and damage to the cutter bar, chain, and bits would result.

One possible method of controlling the rotation and translation of the cutter bar is to mount it on a four-bar linkage, as shown in Figure B.5. In this system, the rotation of pivot point A about pivot point 0 both rotates and translates the cutter bar with one single motion. Another method of controlling cutter bar tilt is to translate and rotate the cutter boom assembly. Figure B.6 shows ths concept in which the boom can rotate 11 degrees while translating 1 foot to either side. Rotation is accomplished by a rotary actuator; translation is controlled by hydraulic rams.

Figure B.7 shows an engineering model built at CEL of a NAVFAC trenching concept (Ref 30). Figure B.7a shows the trencher with the cutter bar in the stowed position. The cutter bar angle can be set by extending the hydraulic ram (Figure B.7b). Cutter depth is then controlled by sliding the cutter bar into the ocean bottom (Figure B.7c). Trench depth and cutter bar angle are controlled by using the concept discussed earlier and shown in Figure B.3. This concept was chosen over the four-bar concept because it gives maximum rigidity for the least amount of weight. Figure B.8 shows how the cutter bar tilt is maintained vertically in the trench while the vehicle is negotiating obstacles.

This system uses the articulated boom (rotation and translation) concept of Figure B.6.

Figure B.8a shows a rear-on view of the trencher boom and supporting tracks on level terrain. In Figure B.8b, the tracks are shown negotiating a 2-foot obstacle, causing the chassis to roll. However, the trencher boom assembly is maintained vertically in the trench. Note that the cutter assembly has been rotated counterclockwise and translated to the left with respect to the chassis.

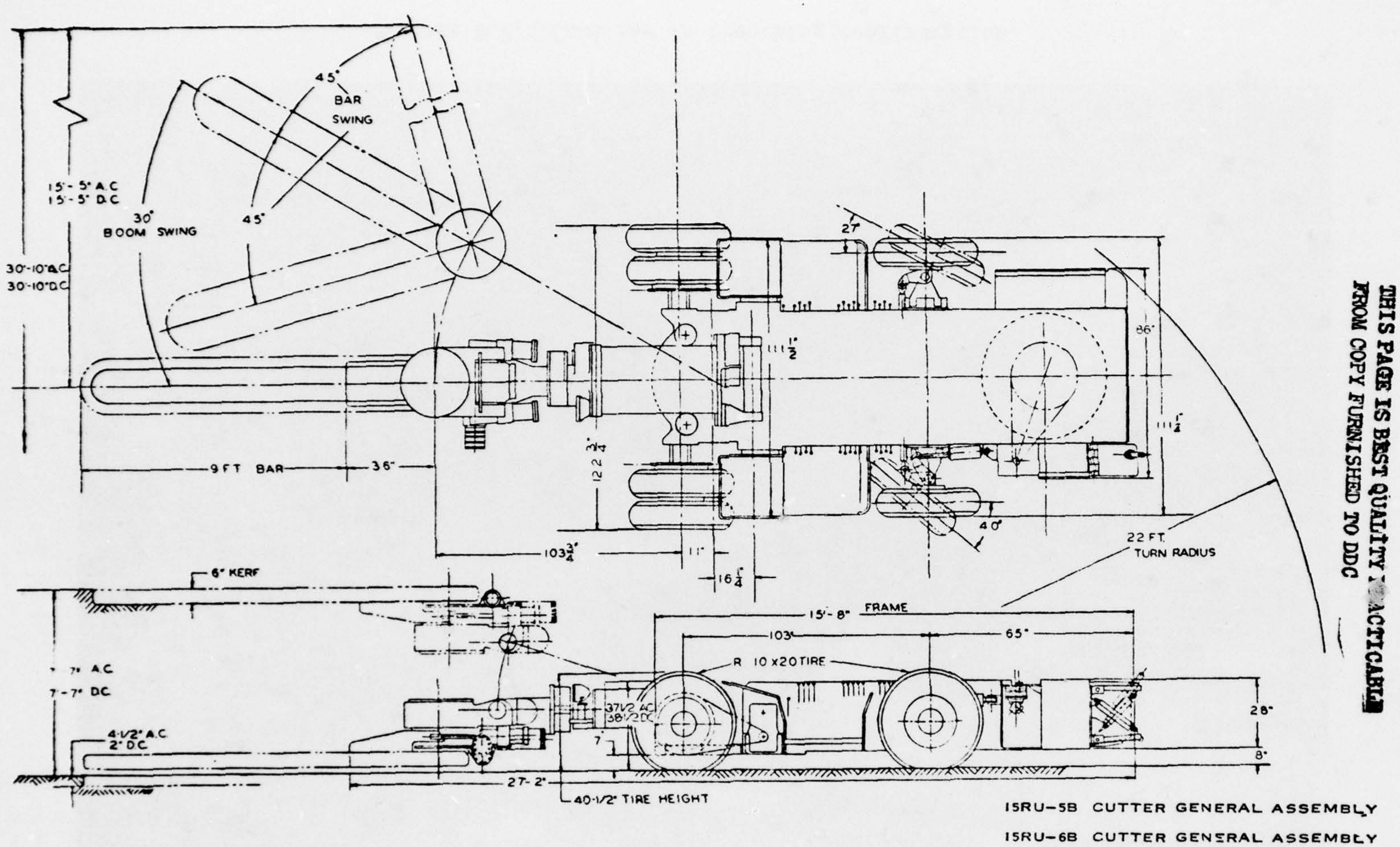

Figure B.1. Coal saw.

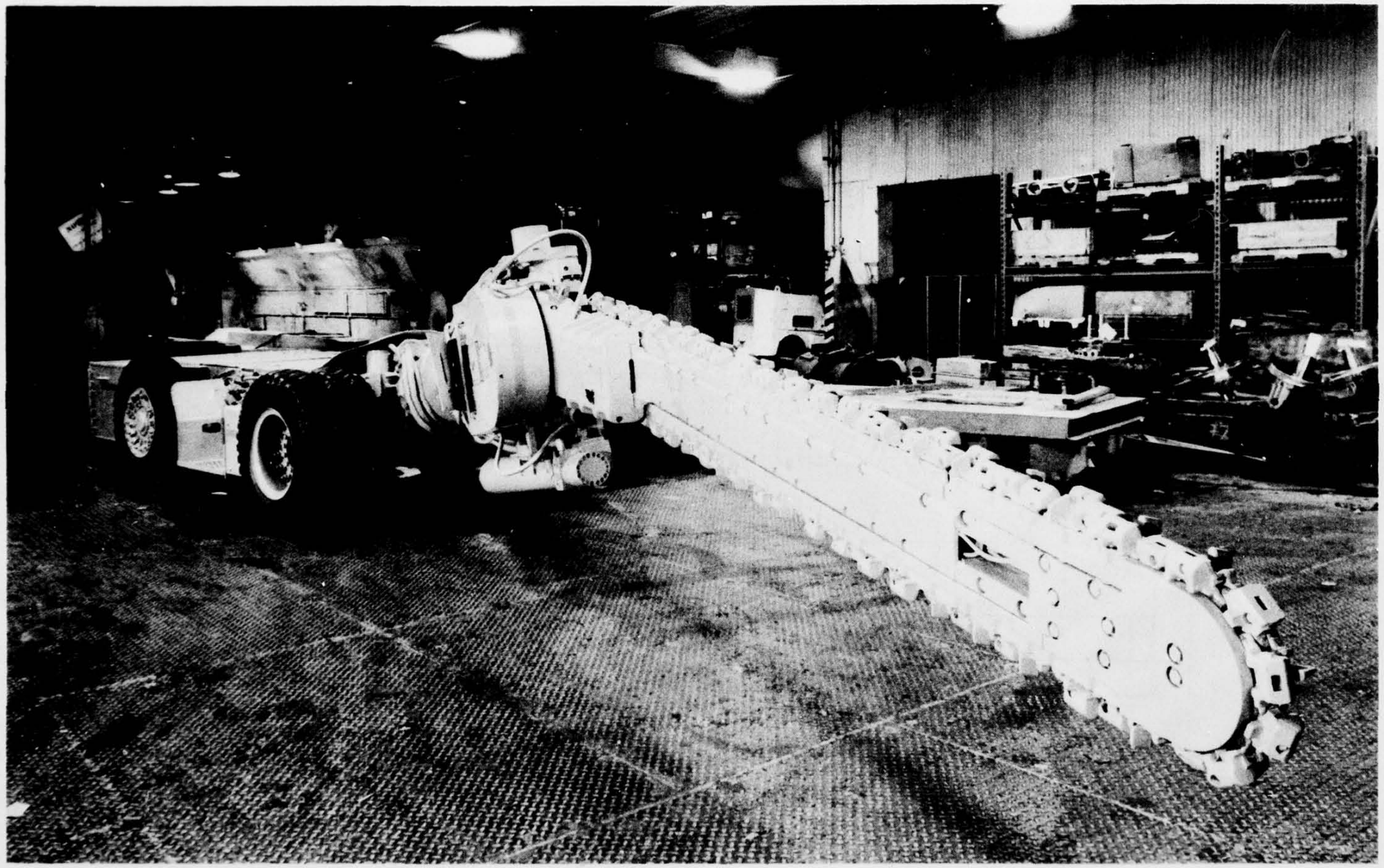

Figure B.2. Coal saw in trenching configuration.

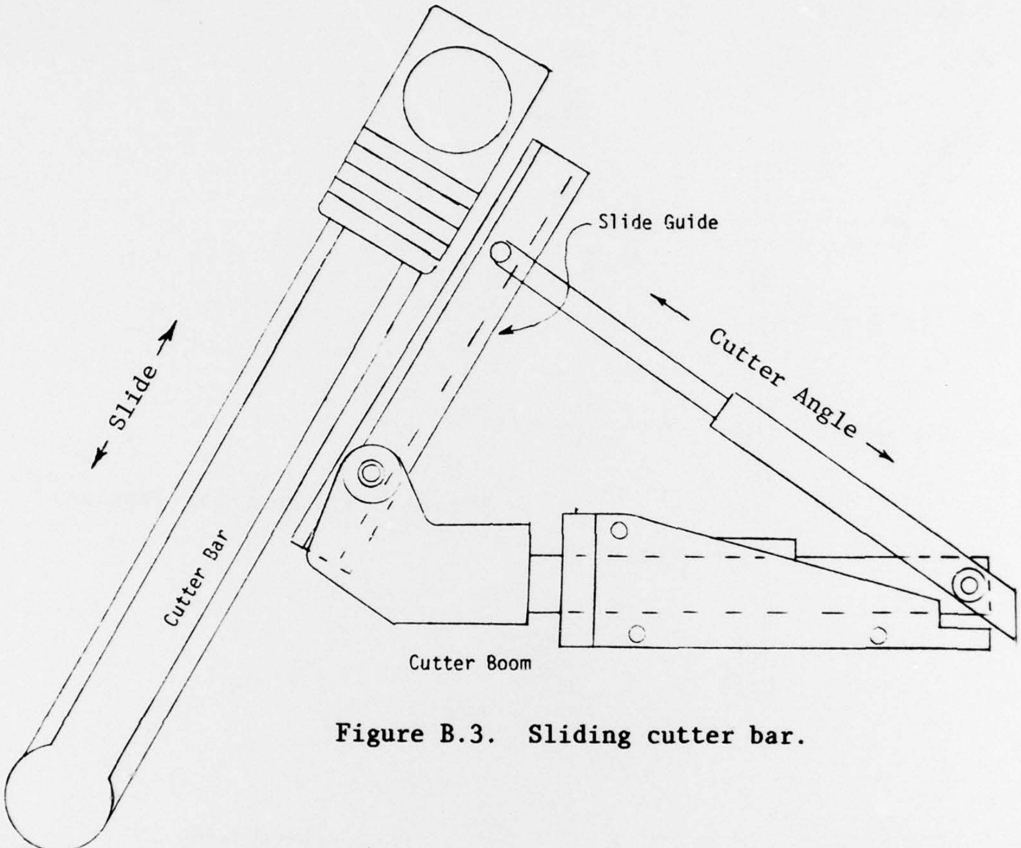

Figure B.3. Sliding cutter bar.

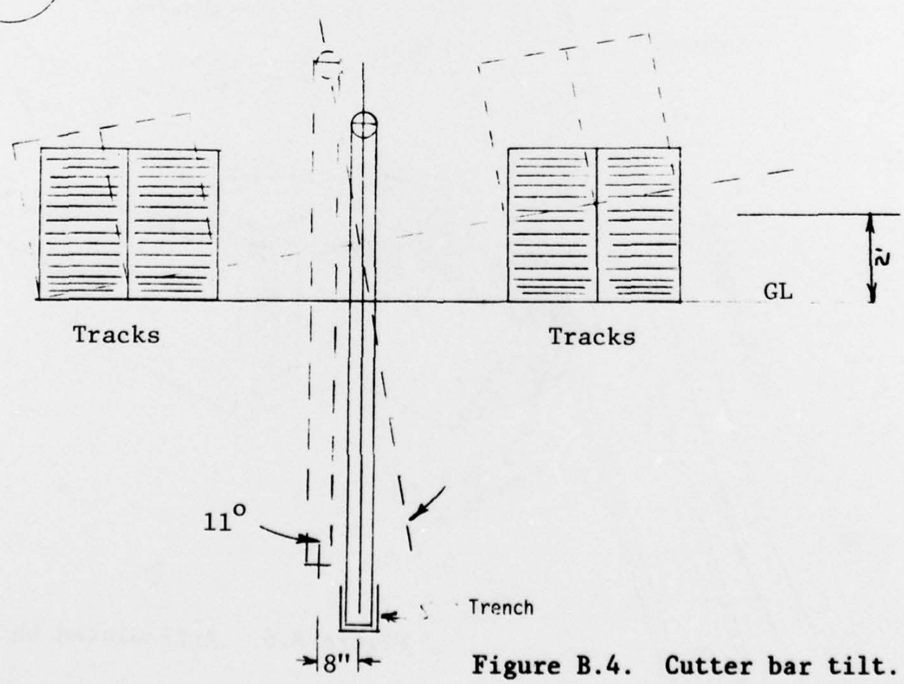

Figure B.4. Cutter bar tilt.

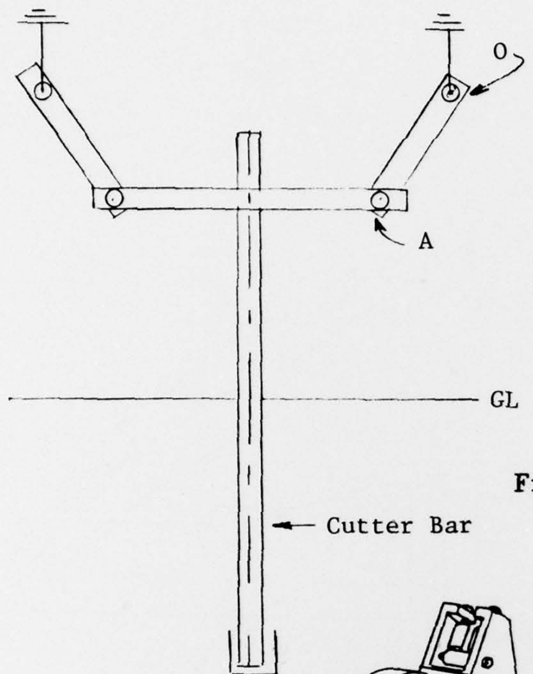

Figure B.5. Four-bar linkage.

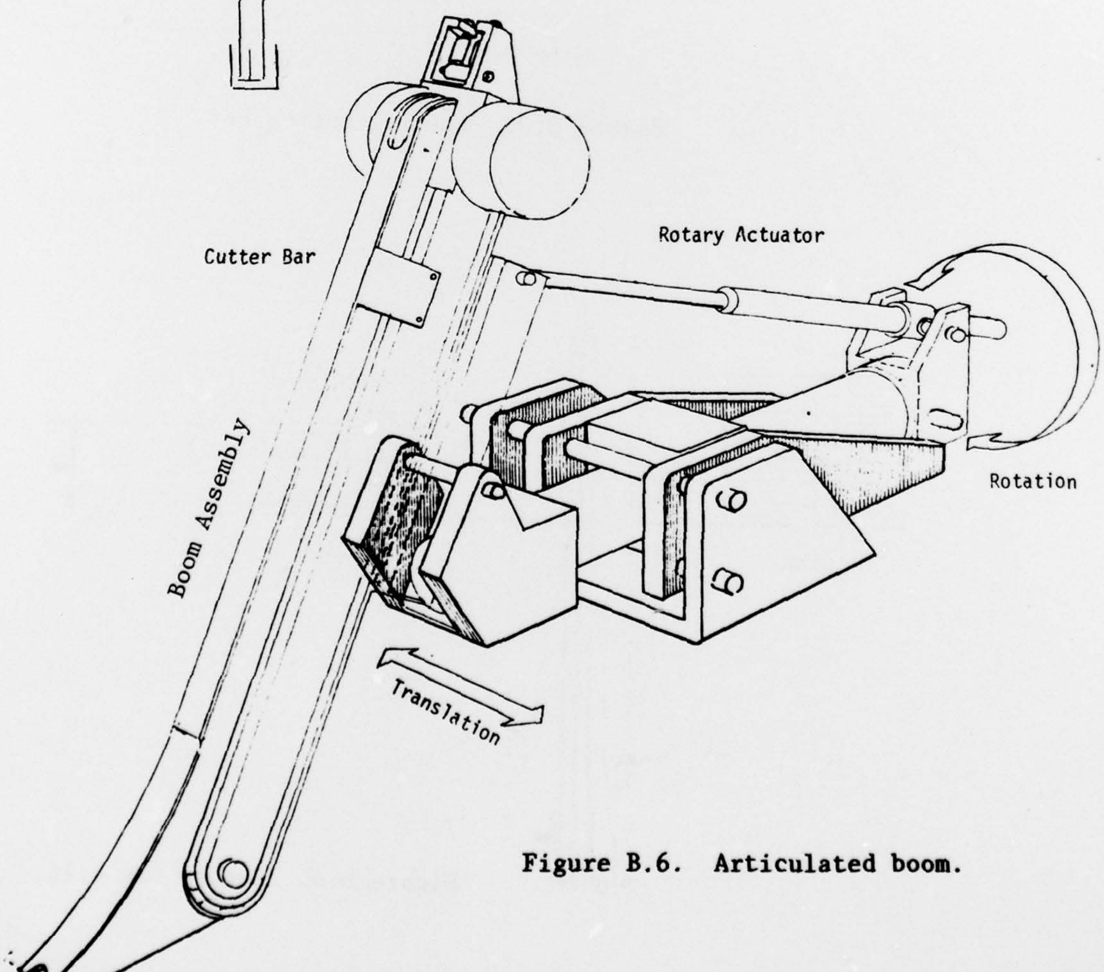

Figure B.6. Articulated boom.

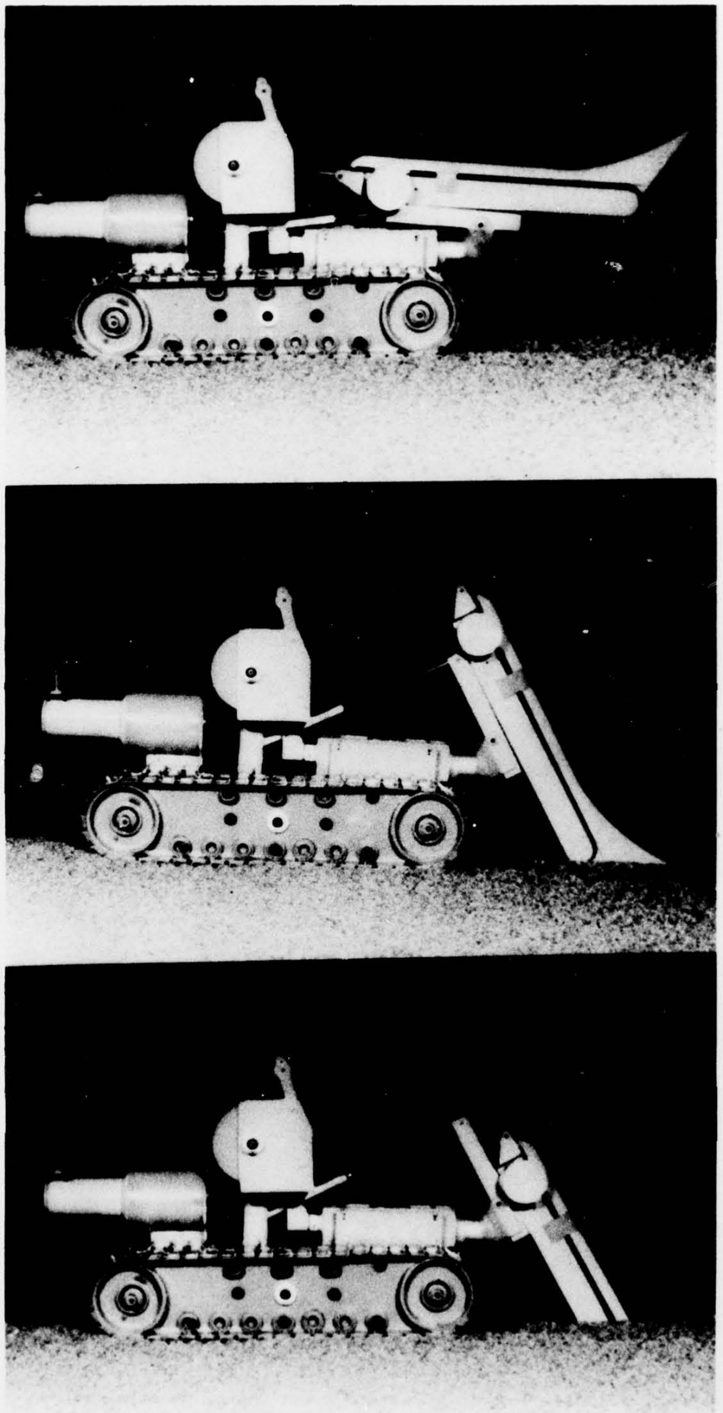

Figure B.7. CEL trencher concept (side view).

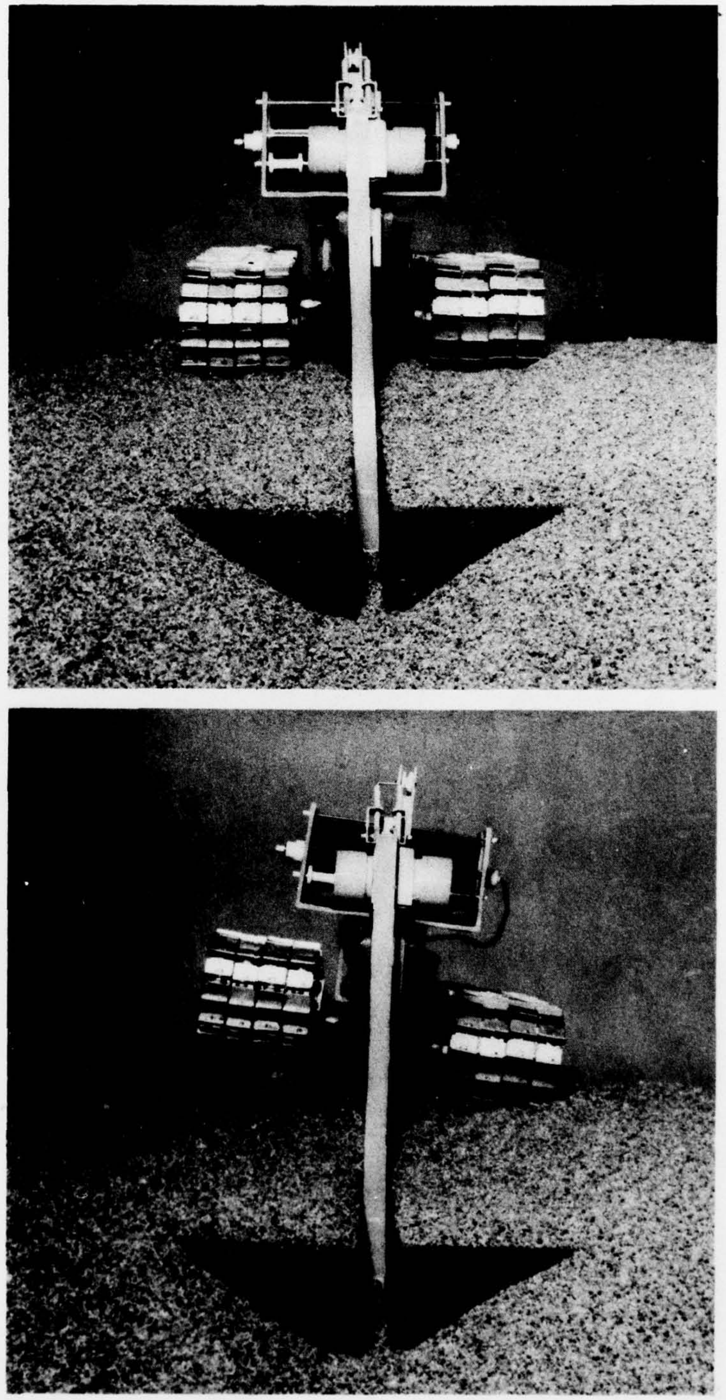

Figure B.8. CEL trencher concept (rear view).

List of Symbols

A	Area, ft^2
C	Speed of sound
D	Performance index
D_J	Jet standoff distance, in.
d	Depth of trench, in.
E	Specific energy, in.-lb/in.^{3}
K	Total power distributed to the cutting mechanism, %
ℓ	Tool chipping depth, in.
P	Pressure, psi
$\dot{P}$	Power input to machine, hp
S	Cutter bit spacing, in.
U	Forward traverse velocity, ft/min
U_t	Tangential tool speed, deg
V	Jet Velocity, ft/sec
$\dot{V}$	Volumetric removal rate of excavated material, in.^{3}
$\dot{Z}$	Material removal rate, ft^3/min
β_2	Relief angle, deg
β'_2	Kinematic relief angle, deg
δ	Compressive strength, lb/in.^{2}
ρ	Density of fluid, lb/ft^3
σ	Compressive strength, psi
ϕ	Cutter bar angle, deg

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